MAPS pixel option and potential R&D

Michael P. McCumber
Los Alamos National Laboratory

Inaugural 'SPhenix/New RHIC Detector' Collaboration Meeting

from Thursday, December 10, 2015 at **08:30** to Saturday, December 12, 2015 at **18:00** (US/Eastern)
at **Rutgers University (BSC Center Hall)**

SPHENIX

Los Alamos
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EST. 1943

MA… nd

Inaugural 'SP… ation Meeting

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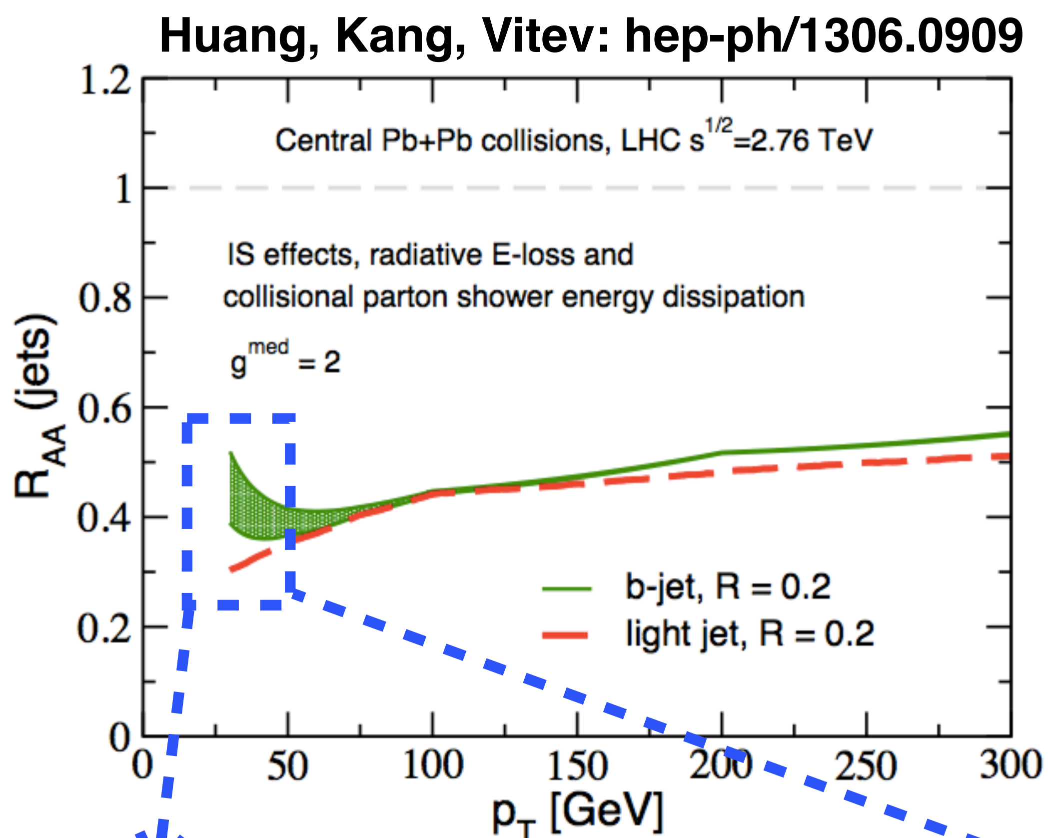
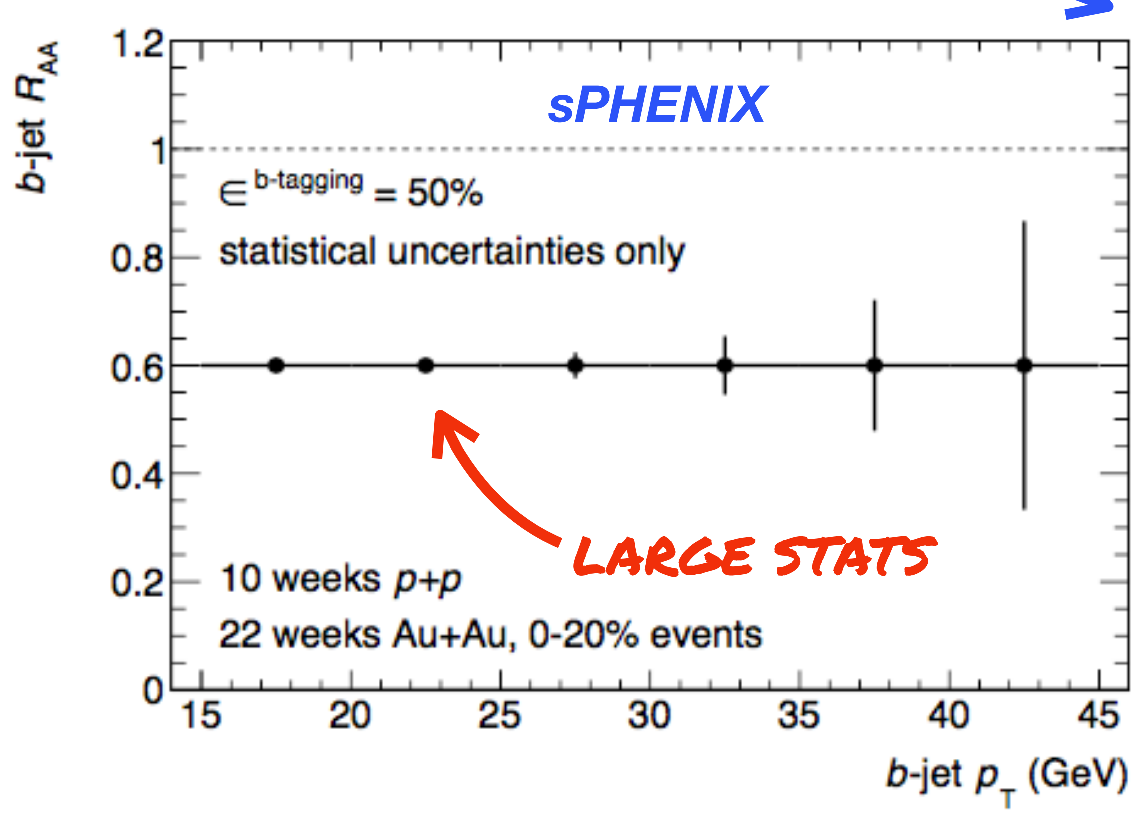
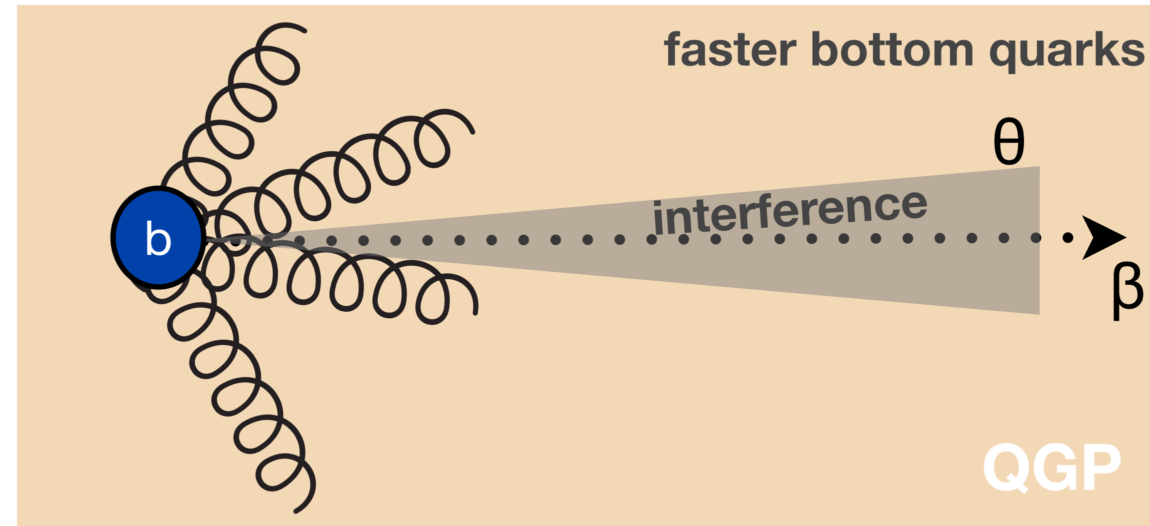
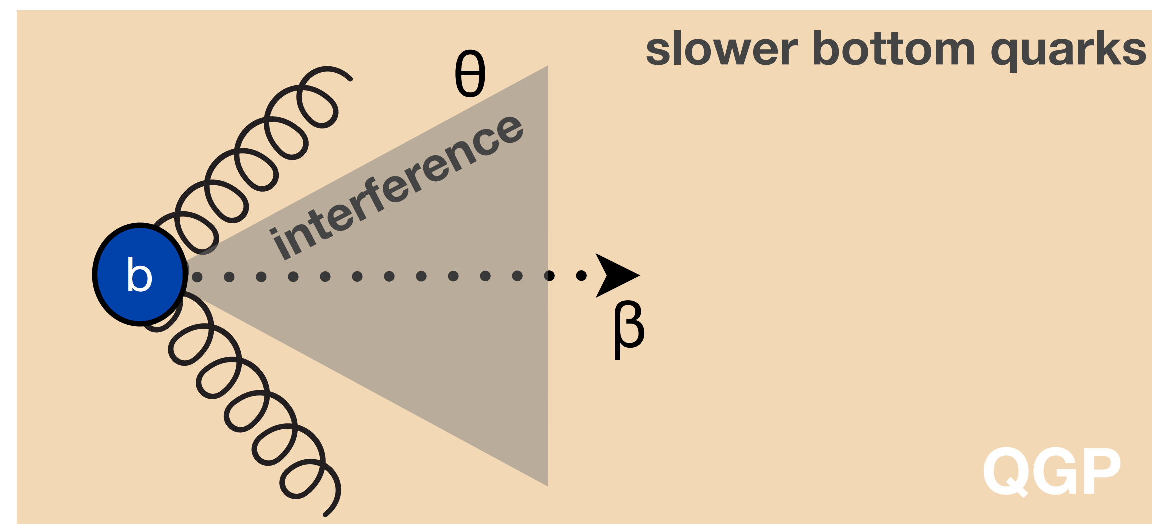
EST. 1943

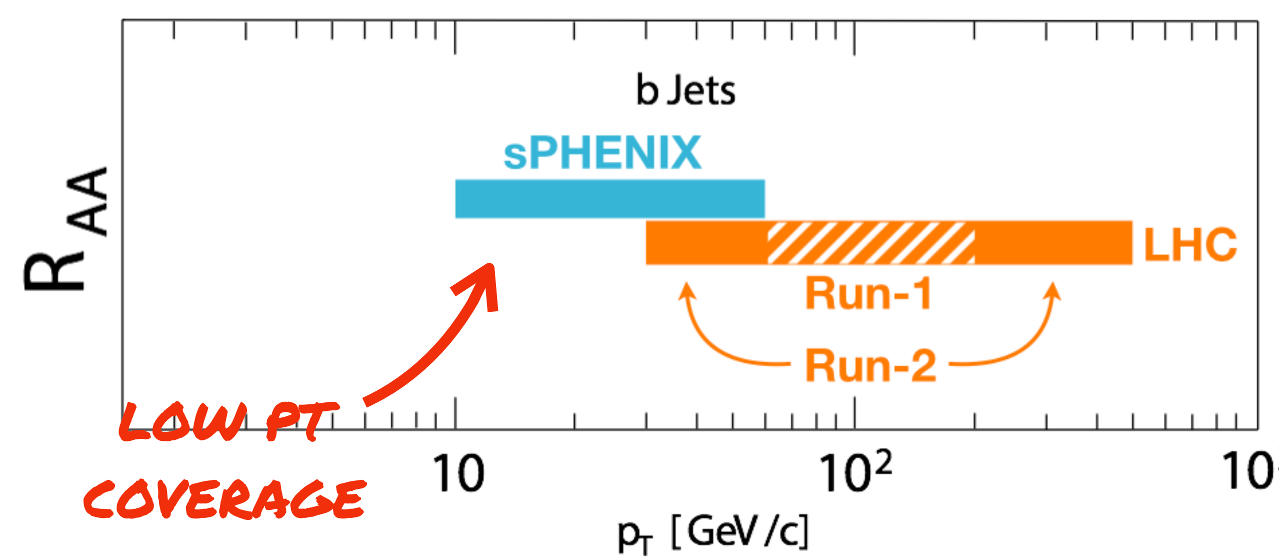
B-jet Physics: Energy Loss



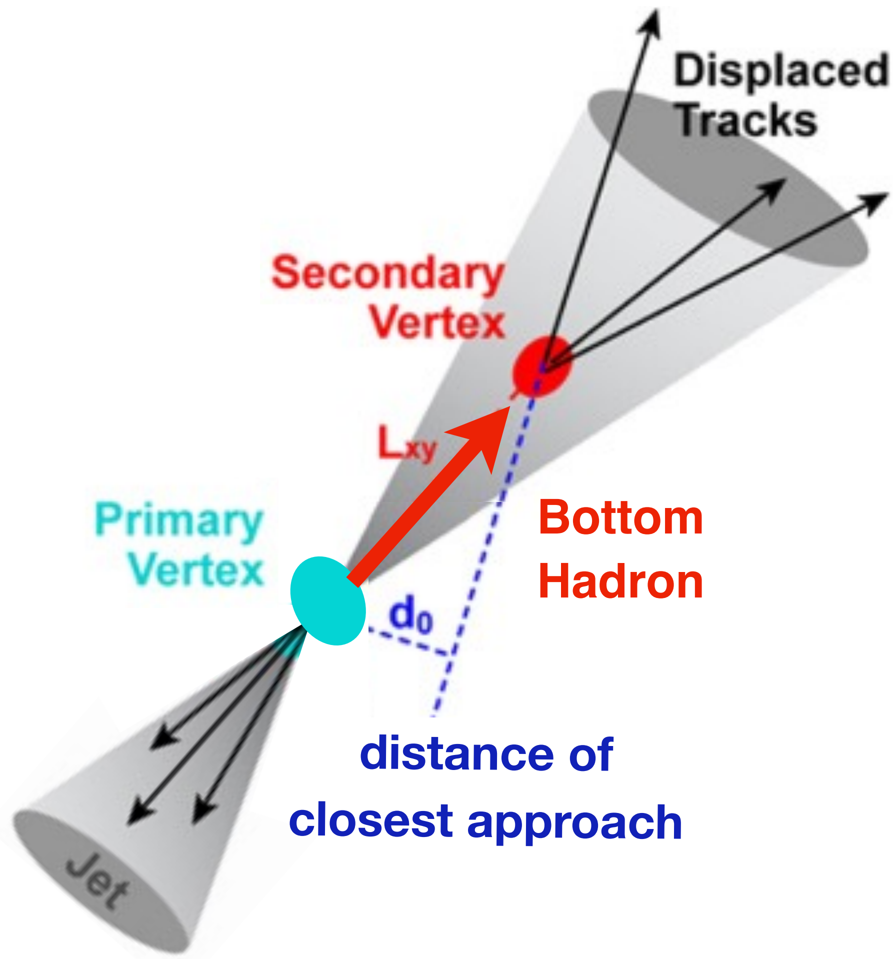








B-jet Identification Methodology



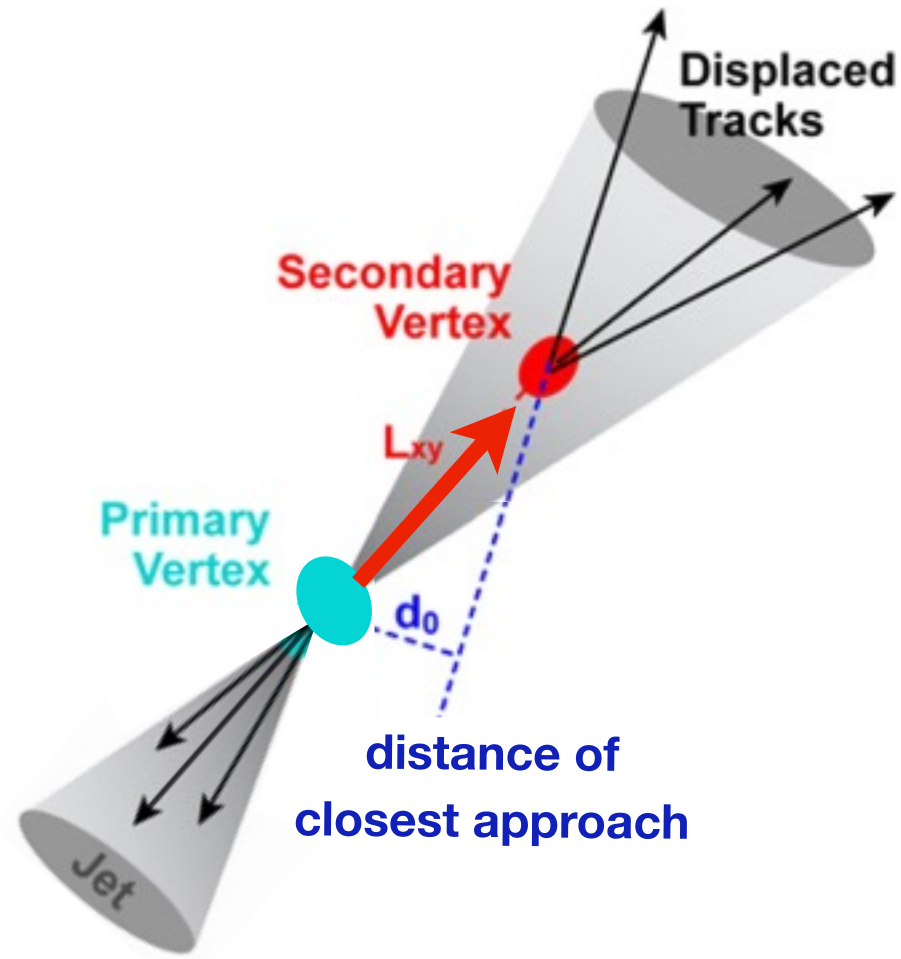
sPHENIX should have access to 3 different techniques for heavy-flavor identification:

(1) Semi-leptonic decay
(2) Multiple Large DCA tracks
(3) Secondary Vertex Mass

Big push from DVP for sPHENIX proposal

Unexplored thus far!

B-jet Identification Methodology



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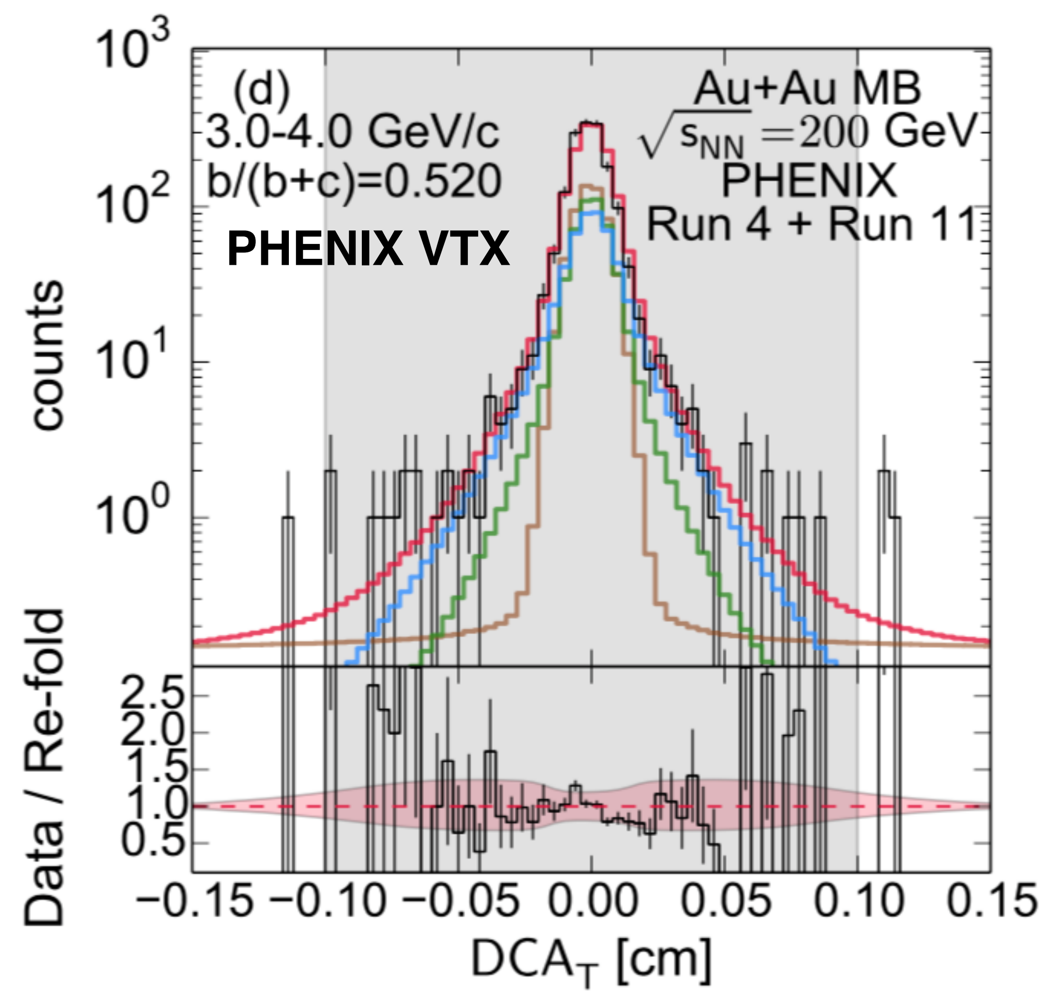
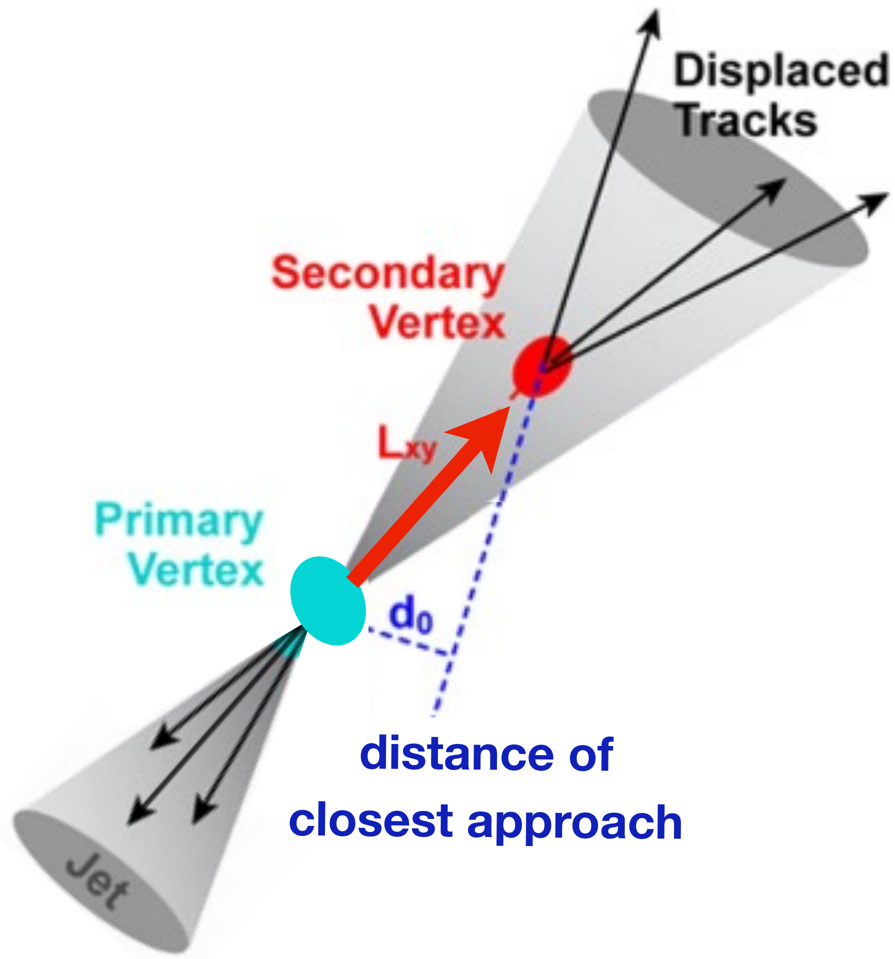
Semi-leptonic decay requirements:

Electron identification at large p_T

Narrow primary electron DCA distribution



B-jet Identification Methodology



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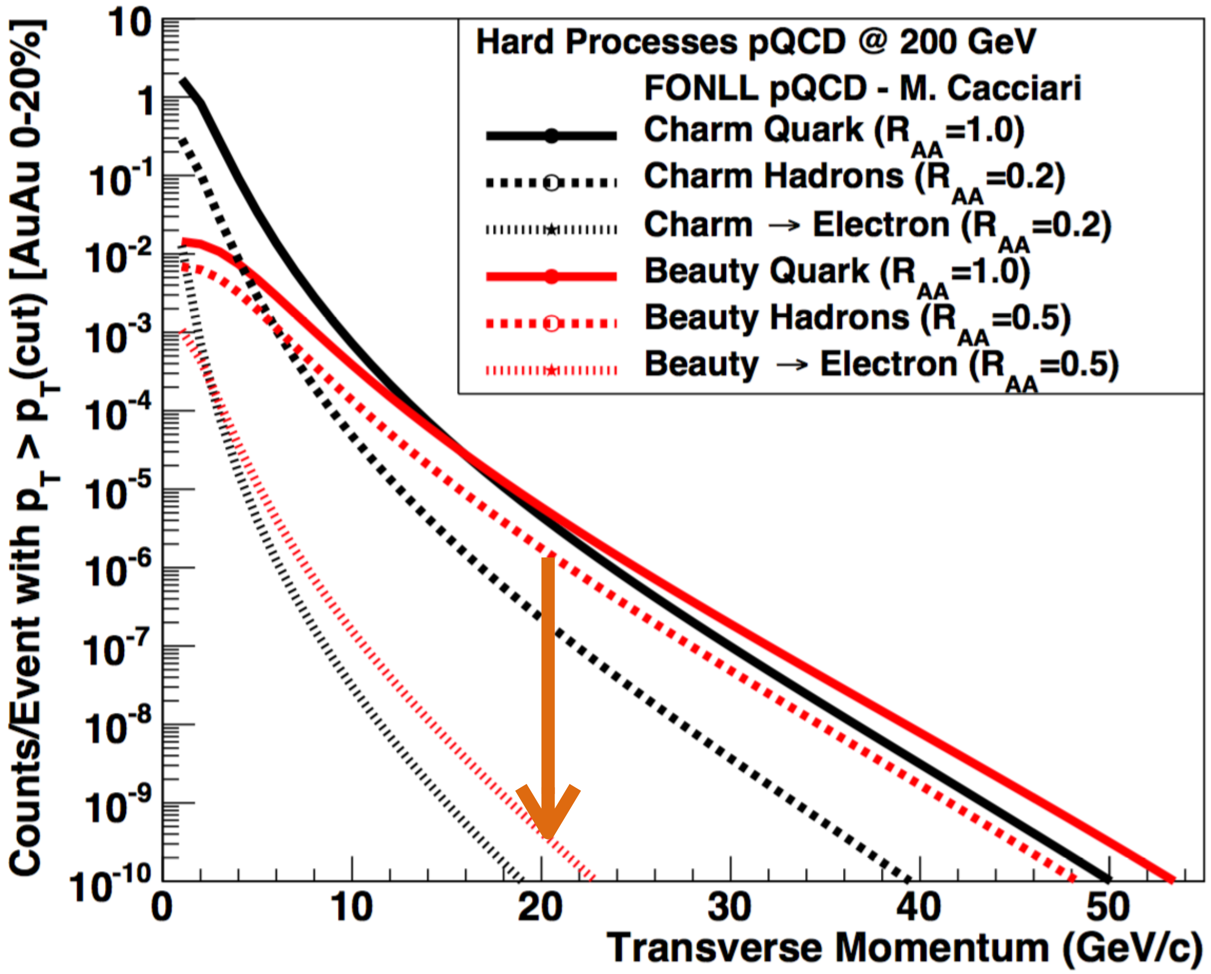
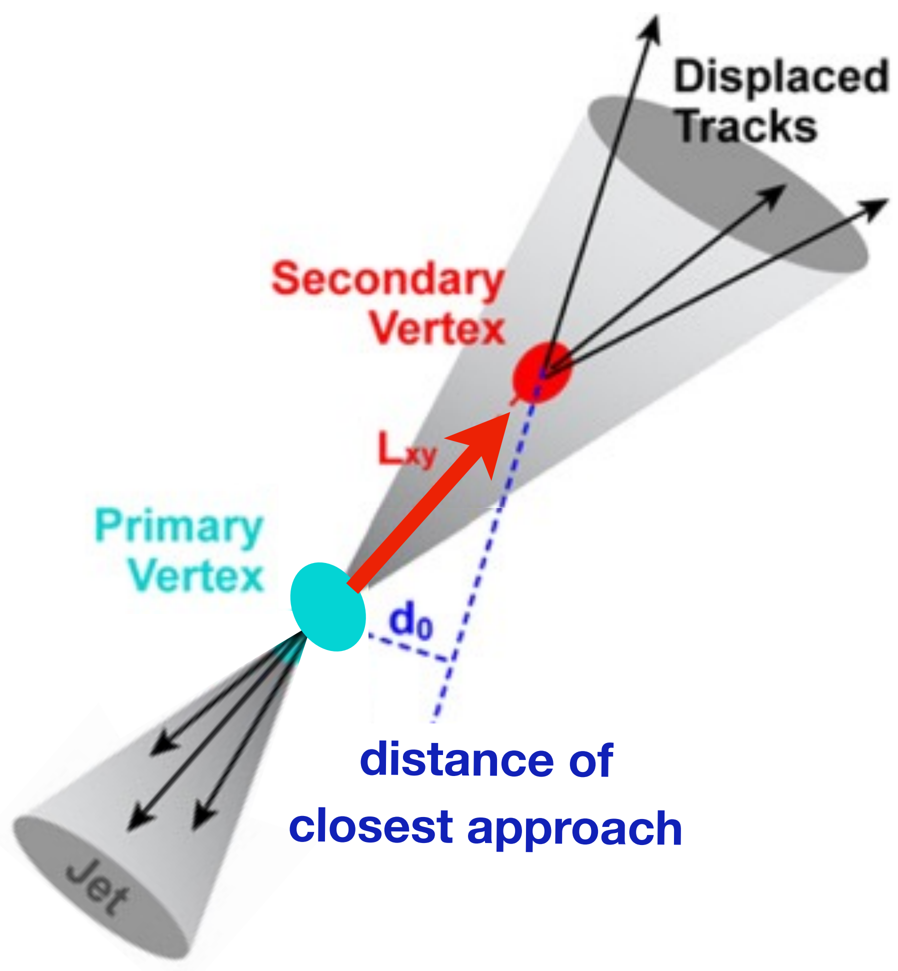


Semi-leptonic decay requirements:
- Electron identification at large p_T
- Narrow primary electron DCA distribution

Downside: Large reduction in B-jets if only the semi-leptonic decay channel is used

Unclear if this is a viable route to b-jets

B-jet Identification Methodology



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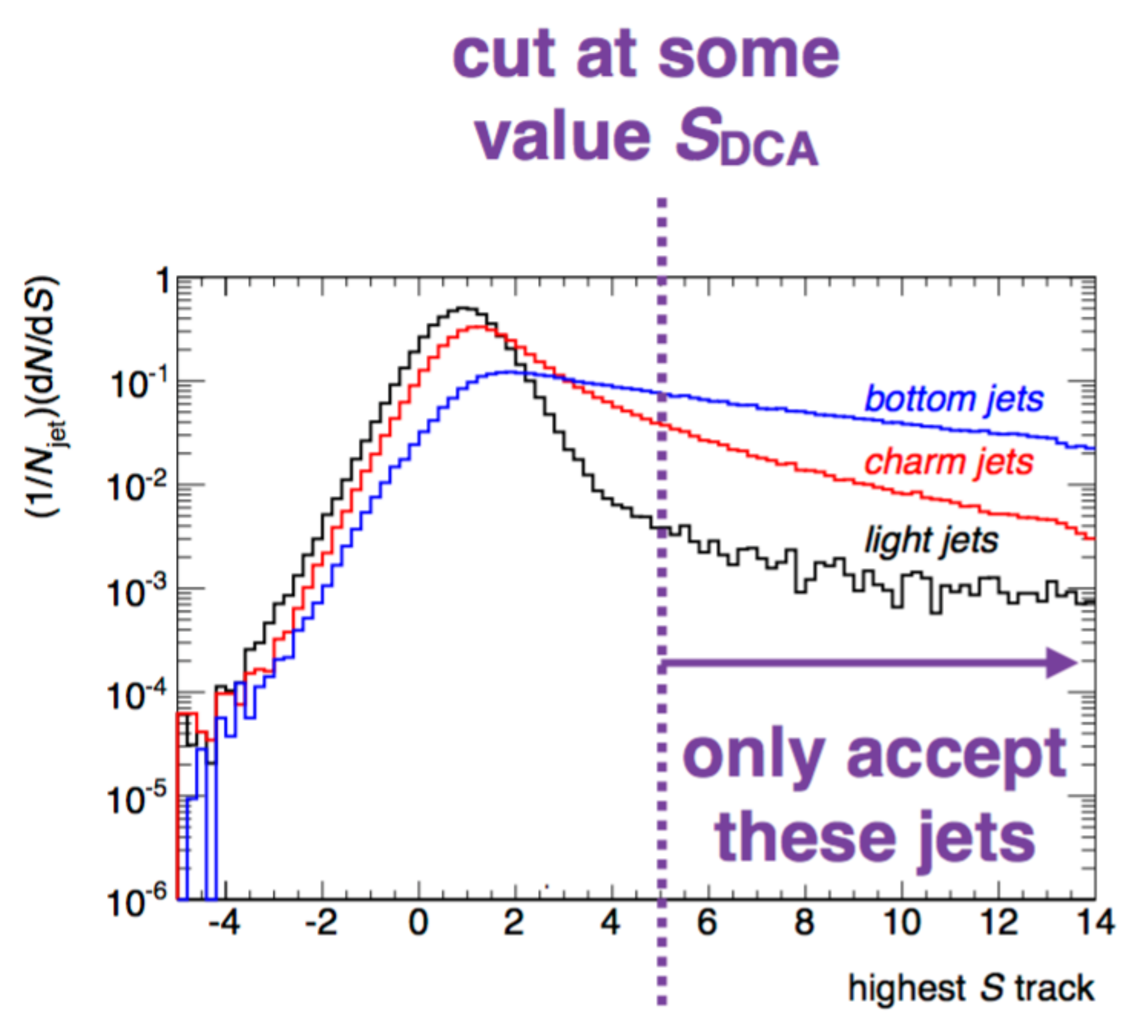


Track Counting requirements:

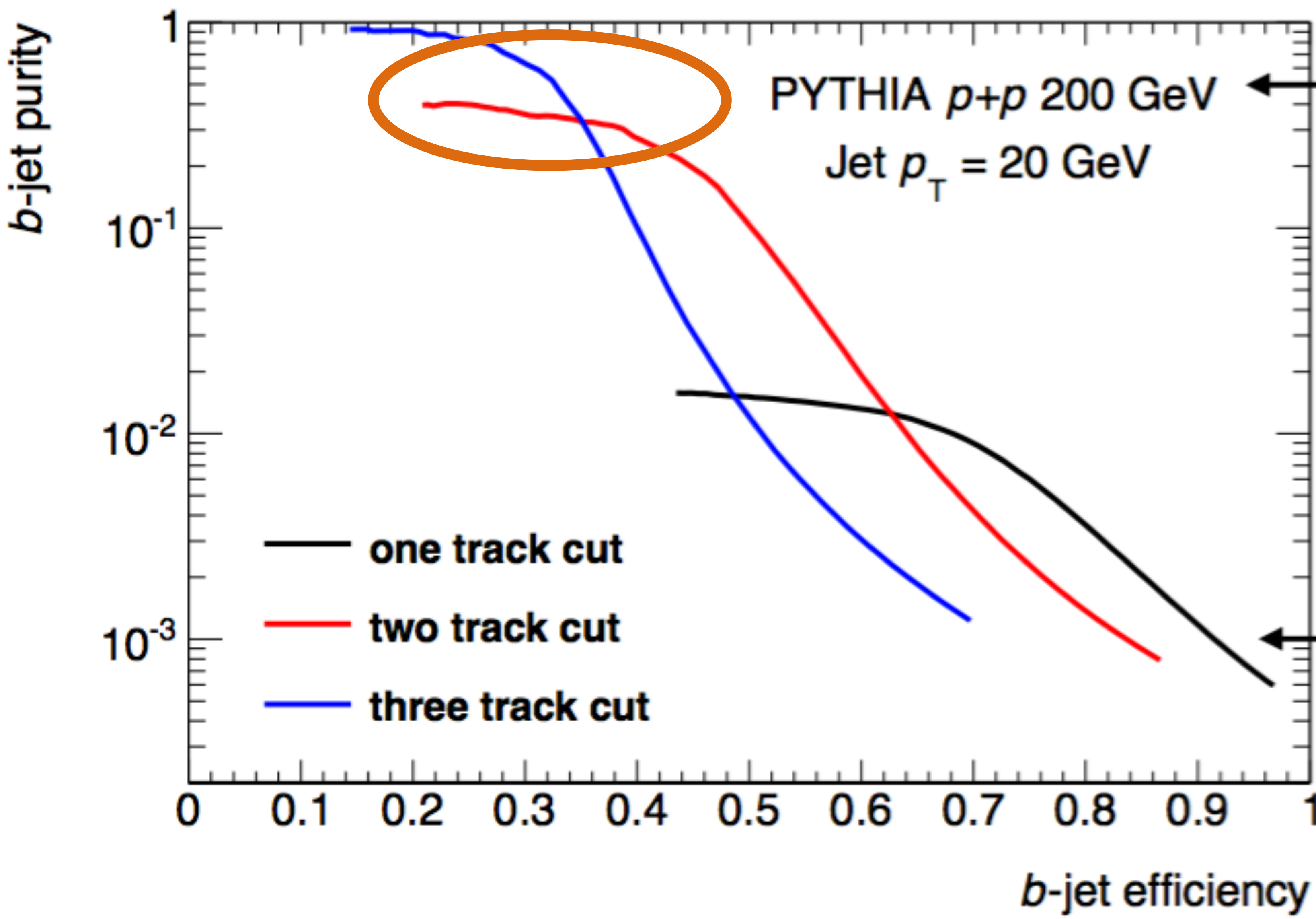
Large single particle reconstruction efficiency, $\sim\epsilon^N$

Narrow primary hadron DCA distribution (<70um)

B-jet Identification Methodology

from the April Review…

b-jet performance in *p*+*p*

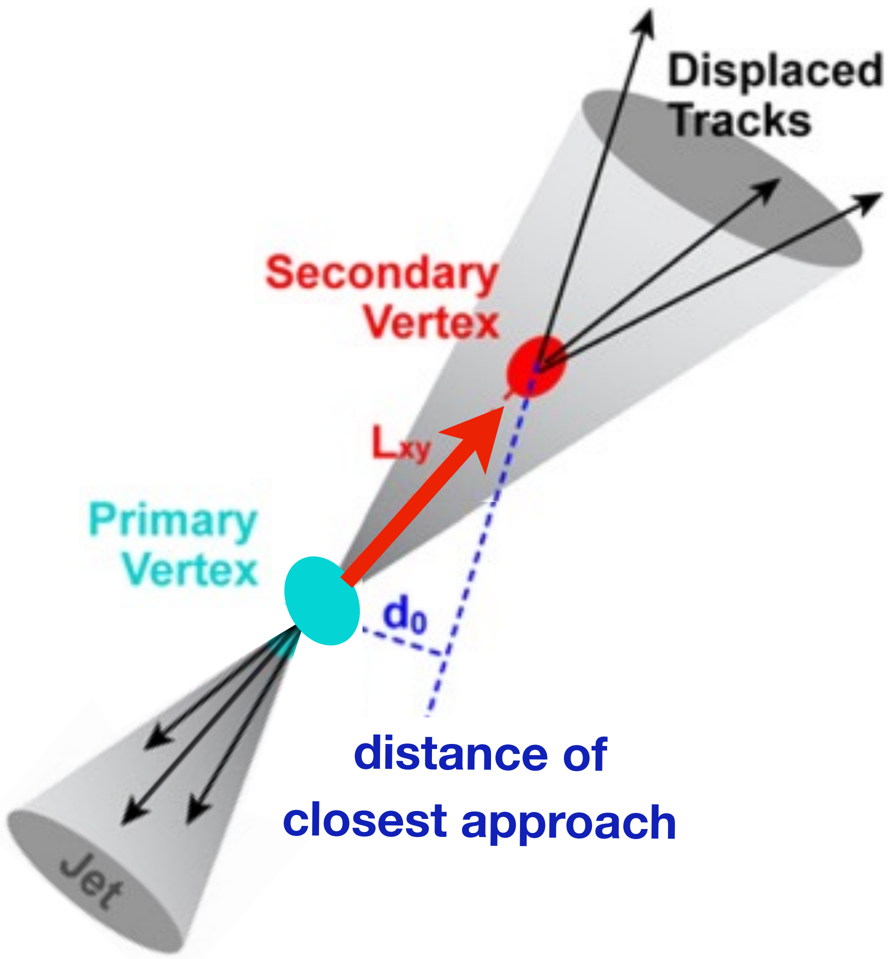


Purity ~ 0.5 is achievable at reasonable efficiency!

Purity $<10^{-3}$ before any cuts!

P vs. **E** curves for requiring **1**, **2** or **3** tracks with S_{DCA} above some minimum value

B-jet Identification Methodology



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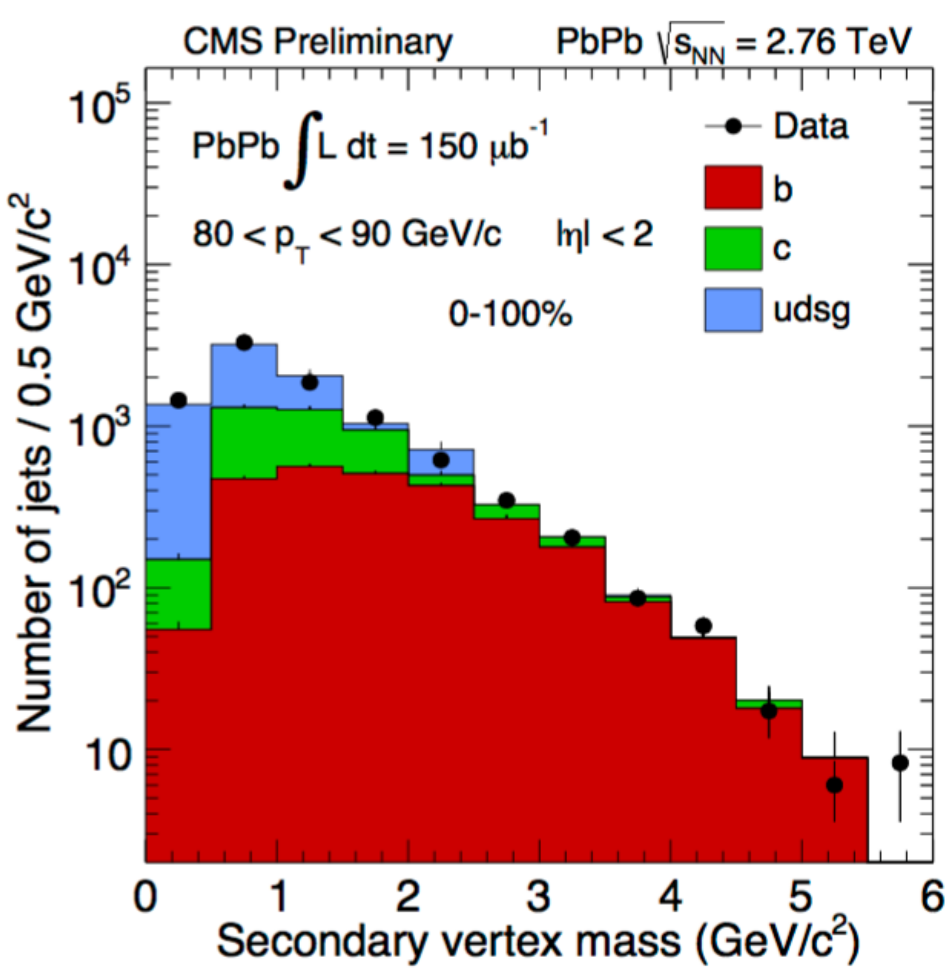


Secondary Vertex requirements:

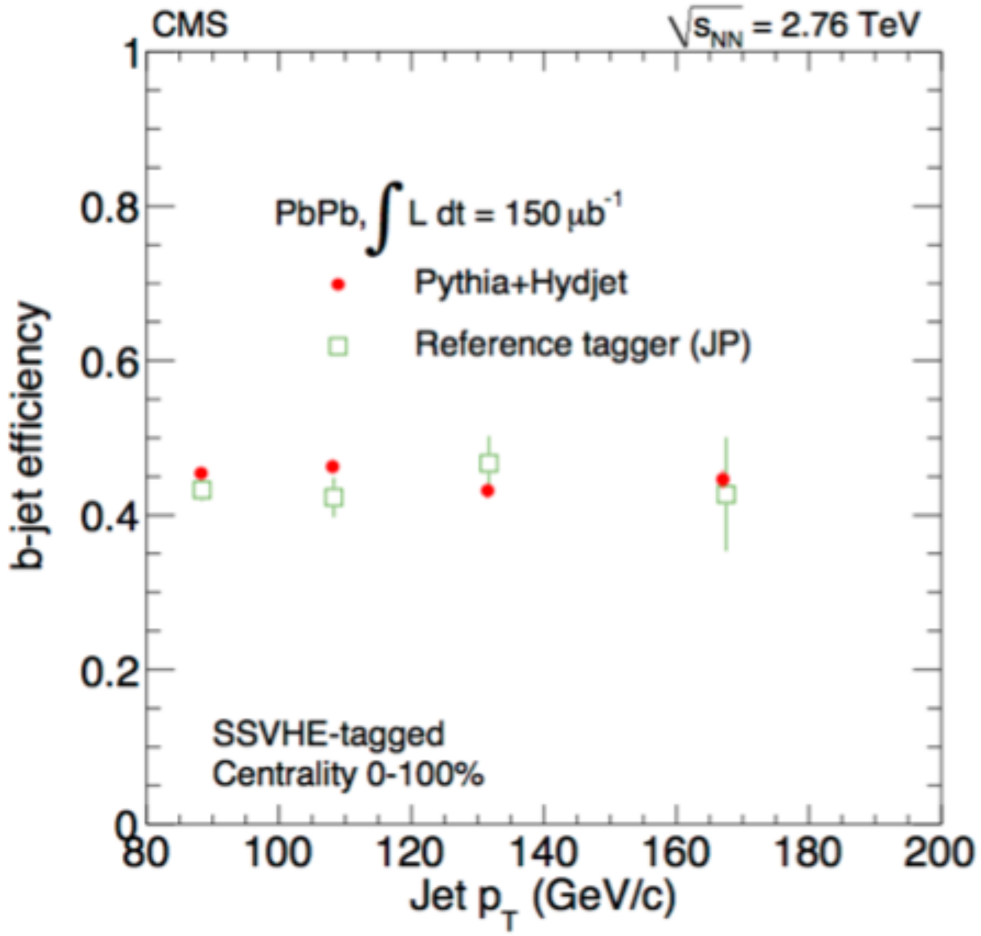
Large single particle reconstruction efficiency, $\sim\epsilon^2$

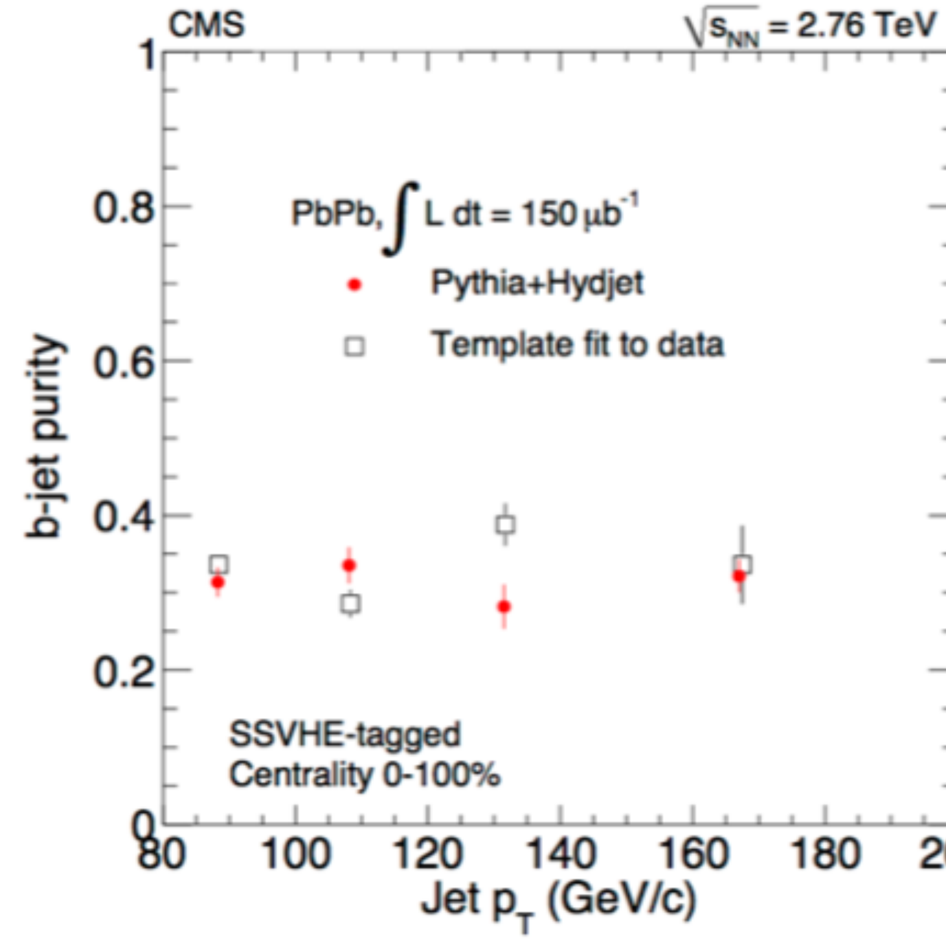
Individual track position resolution

CMS b-jet Performance

from the April Review…

b-jet efficiency and purity in Pb+Pb



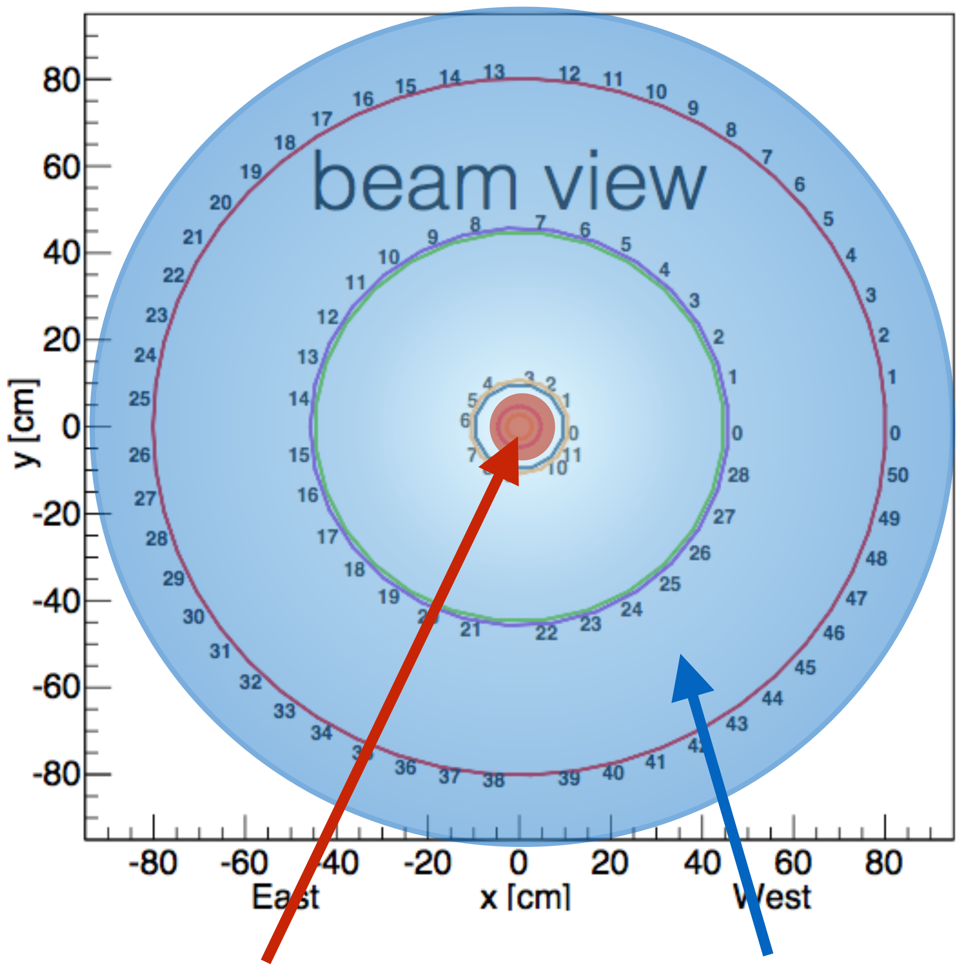


nucl-ex/1312.4198

≈45% Efficiency and *≈35% Purity* in the CMS *b*-jet spectrum in Pb+Pb

➡ comparable to that achievable with 2- or 3-track TrackCounting cuts

Partial Factorization: Inner Tracking Goals



Inner Tracking
(0 < r < 10-30 cm)

Outer Tracking
(10-30 < r < 80 cm)

Inner tracking:

(1) precision track position (DCA, 2nd vertexing)
(2) high resolution collision vertexing
(3) pattern recognition ambiguity breaking

Outer tracking:

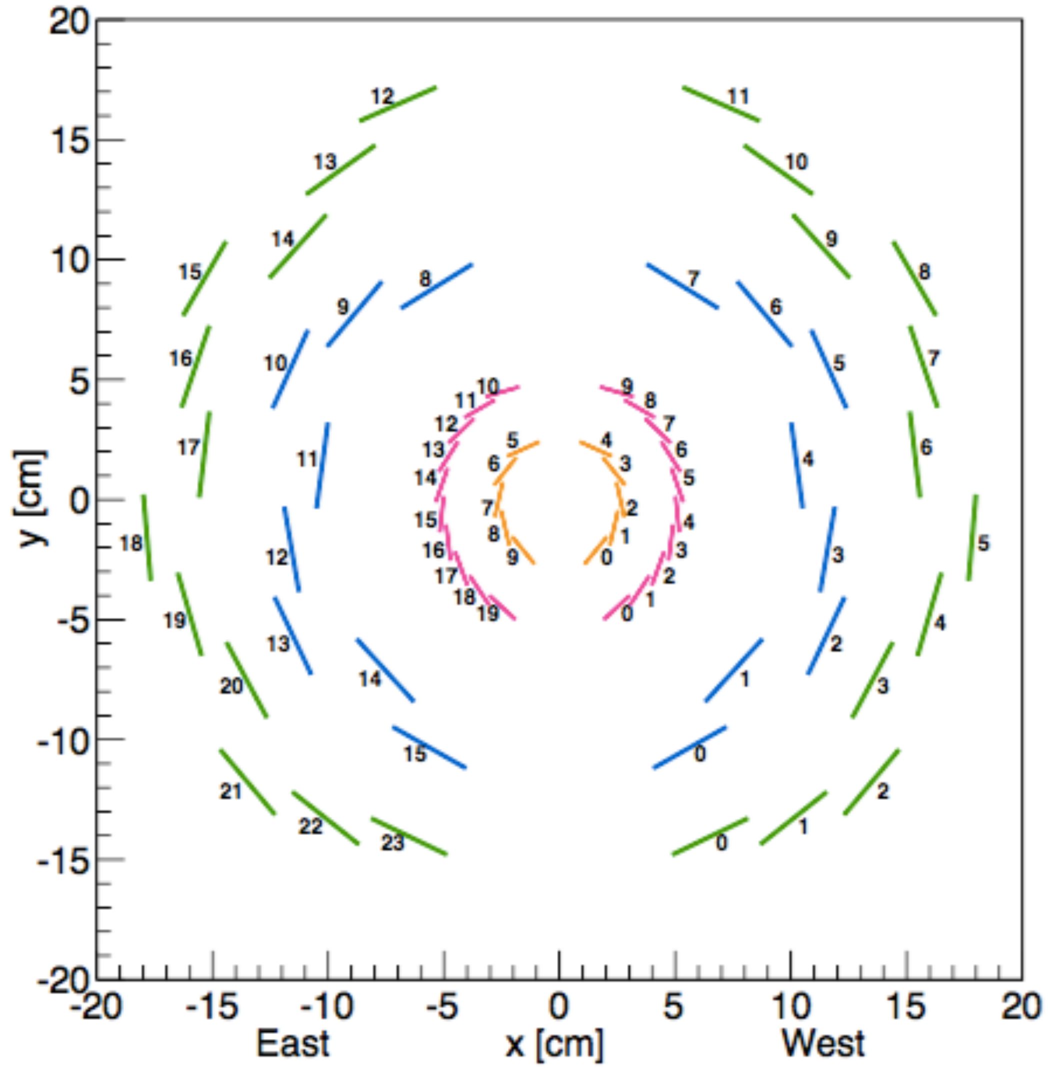
(1) momentum resolution optimization
(2) pattern recognition ambiguity breaking

"The choice between the inner tracker options is independent of the choice of outer tracker technology, and vice-versa."

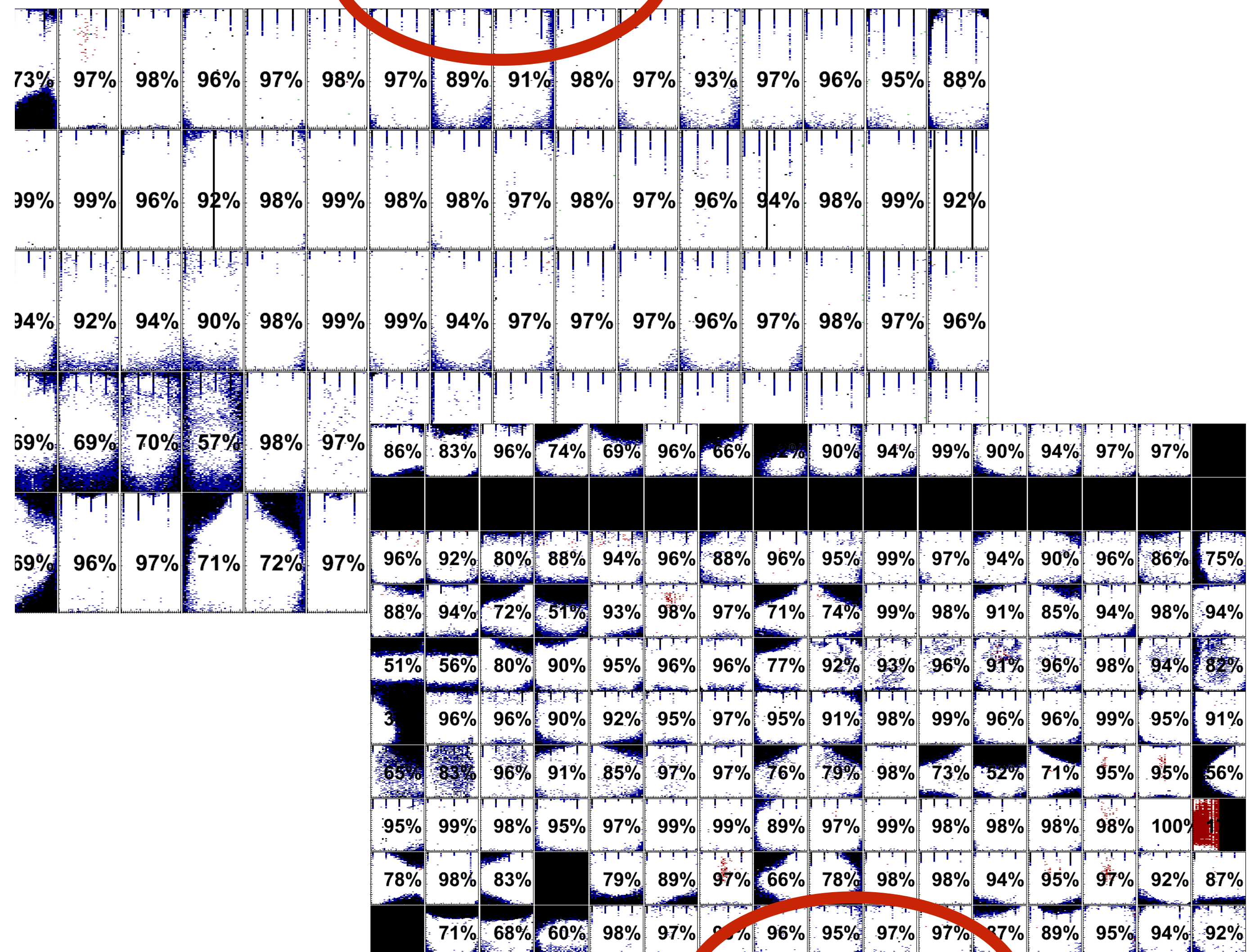
~Early Draft pCDR

For the inner tracking **technology** this is probably true (up to timing requirements), but for the **conceptual design** it is not. An inner + outer tracker will have to perform together with a **low fake rate (solve the basic pattern recognition problem)**.

Tracking Option: Pixels



Pixel Layer 1, 92.5% Active



Pixel Layer 2, 72.5% Active

Station	Layer	radius (cm)	pitch (μm)	sensor length (cm)	depth (μm)	total thickness X_0%	area (m^2)
Pixel	1	2.4	50	0.425	200	1.3	0.034
Pixel	2	4.4	50	0.425	200	1.3	0.059
S0a	3	7.5	58	9.6	240	1.0	0.18

Aside: Other Potential Pixel Reuse Pitfalls

Material thickness (1.3% per layer):

More clear now that with the strip outer layers the material in the inner layers isn't a driver on the Upsilon separation, we should repeat that with the TPC option

Long term evolution will still replace the pixels

One-dimensional optimization in pitch (50um x 425um):

VTX pixels were designed around a DCA-based analysis

Two track intersection probabilities needed for 2nd vertex reconstruction need to be understood

Can the VTX pixels perform the 2nd vertex reconstruction at all?

DAQ Rate:

VTX pixel test saw 14 kHz at 60% live time, somewhat under our 15 kHz ~90% live time readout spec

New hardware could design in the full readout bandwidth

Not sure where the next bottleneck would be, more than a small gain?

Limited TPC integration flexibility:

A finite surface area of VTX pixels is available, we can cover 2.5 cm and 3.6 cm, **no spares**

TPC based tracking starts no closer than 30 cm

3.6 cm to 30 cm is a long jump to make

We may need a tracking layer between 4.4 and 30 cm to break ambiguities in the tracking

Pixel Reuse Pitfalls: Inefficiency

Simultaneous detection with Reused pixels for Track counting methods:

- 1 track = 33% loss
- 2 track = 55% loss
- 3 track = 70% loss

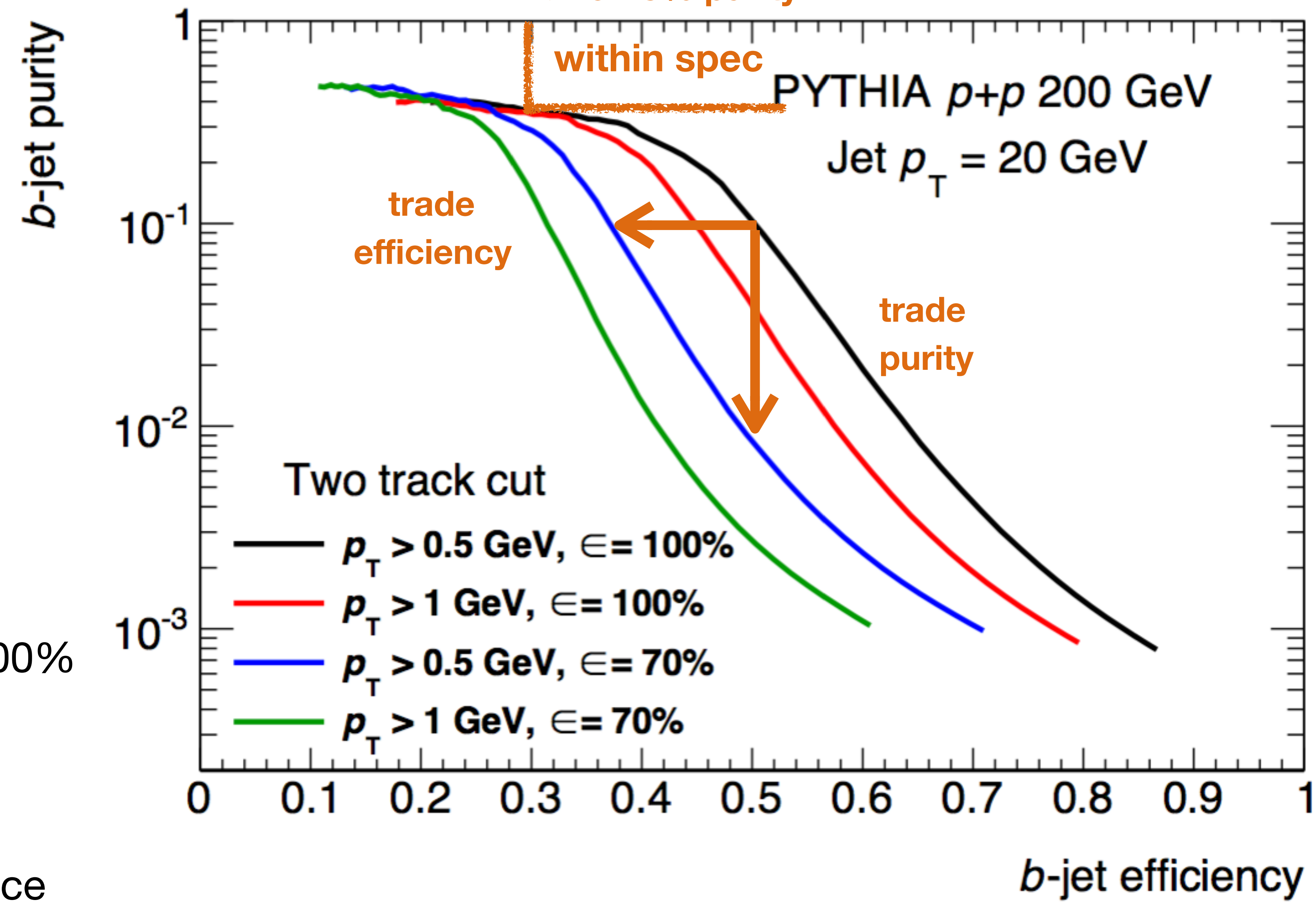
6-hit tracking + vertex fit will likely work for Upsilons, but not for b-jets

Not too far from spec with 100% efficiency

Could restore purity at lower efficiency, but then acceptance corrections will be come painful

Pretty clear: **Three hit methods will be completely lost, needed to get the largest purities!**

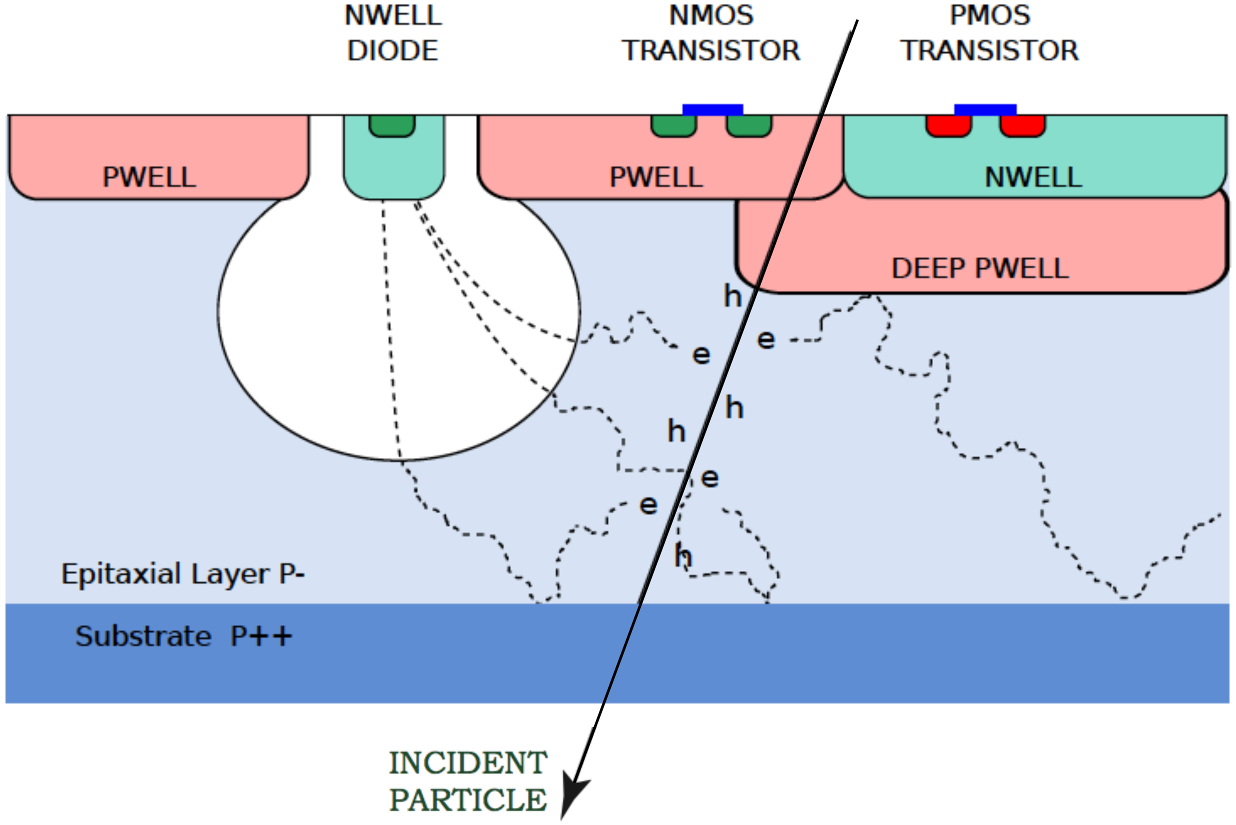
>30-35% efficiency and
>40-45% purity

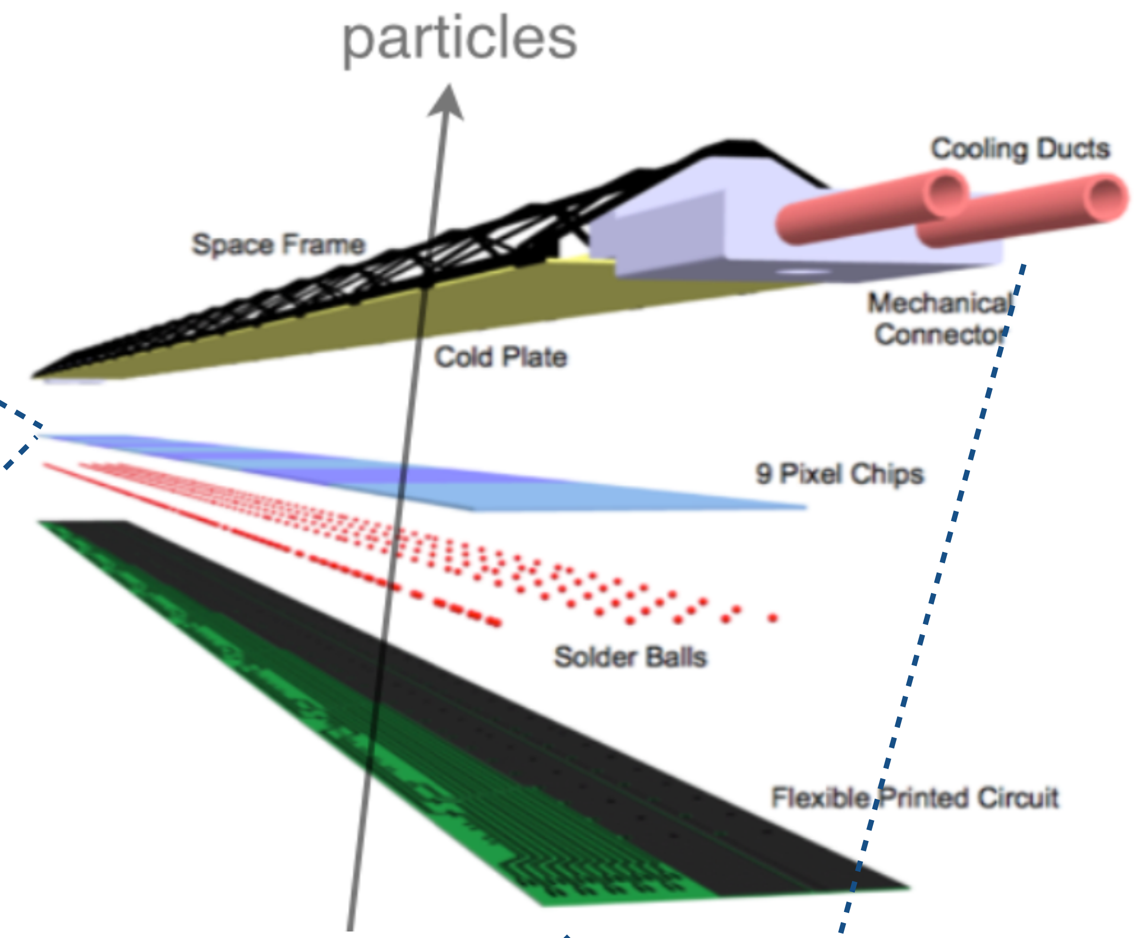


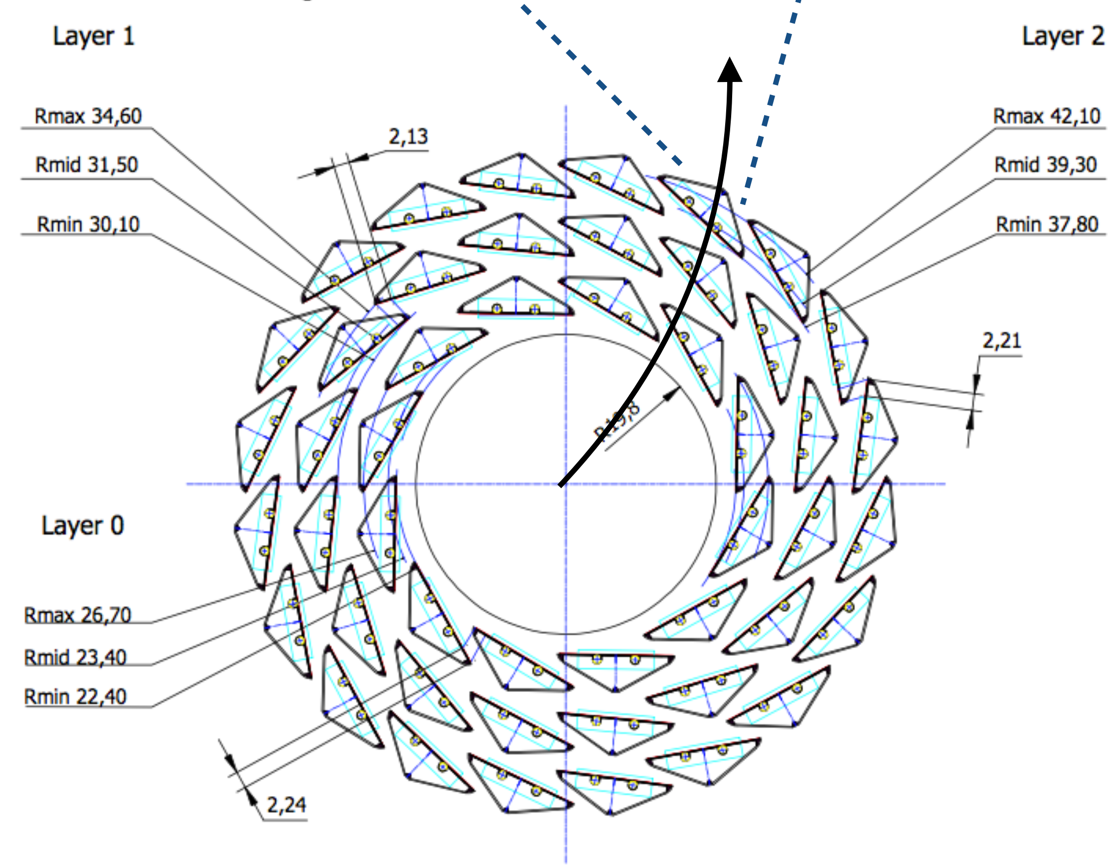
these efficiencies are not included in any sPHENIX b-jet RAA projections

sPHENIX needs new pixel layers!

Tracking Option: MAPS sensors







Inner Silicon Concept:

Thin, fine pitch (<30 um), large efficiency (99.9…%)

Optimizations for material thickness, ~0.3%/layer

Integration time: ~2-4 us

Goal:

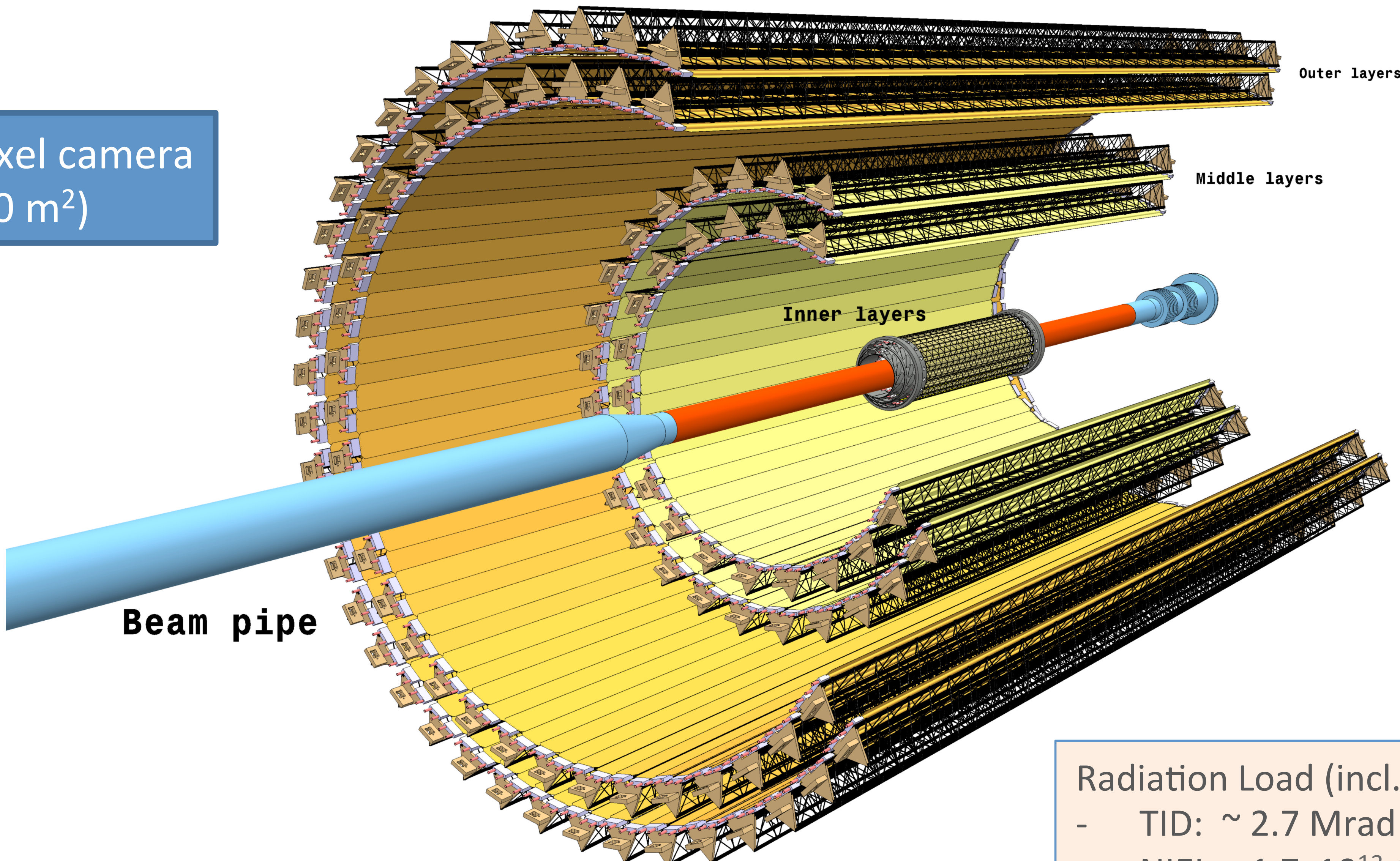
Precision tracking & vertexing for b-jet identification and other tracking duties

Opportunity:

Reuse thin inner tracking layers during the EIC era

ALICE ITS Upgrade

12.5 G-pixel camera
(~10 m^2)



Radiation Load (incl. safety factor 10)
- TID: ~ 2.7 Mrad
- NIEL: ~1.7×10^{13} 1MeV n_{eq} / cm^2

7-layer barrel geometry based on CMOS Sensors

r coverage: 23 – 400 mm

η coverage: $|\eta| \leq 1.22$
for tracks from 90% most luminous region

3 Inner Barrel layers (**IB**)

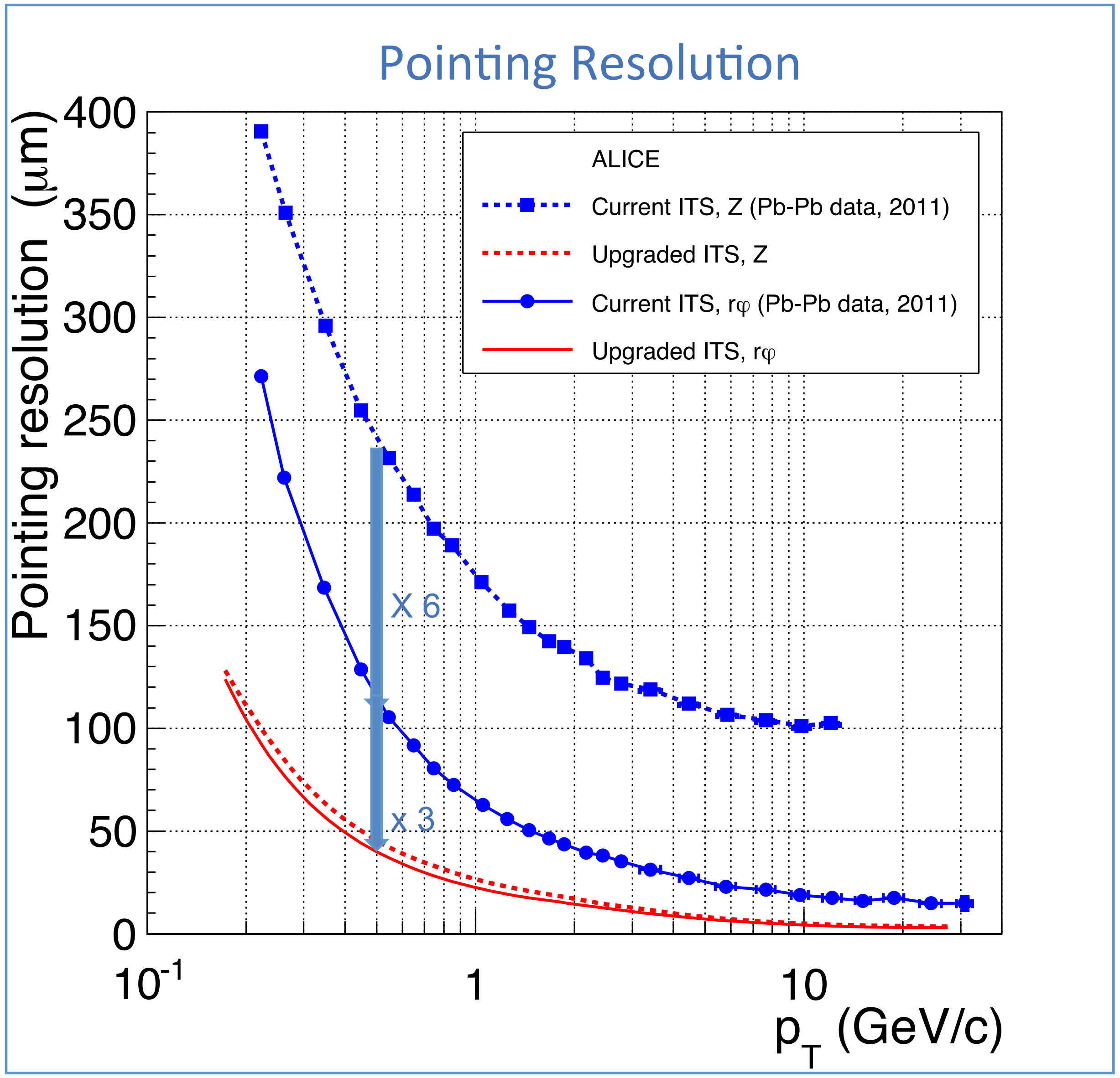
4 Outer Barrel layers (**OB**)

Material /layer : 0.3% X_0 (IB), 1% X_0 (OB)

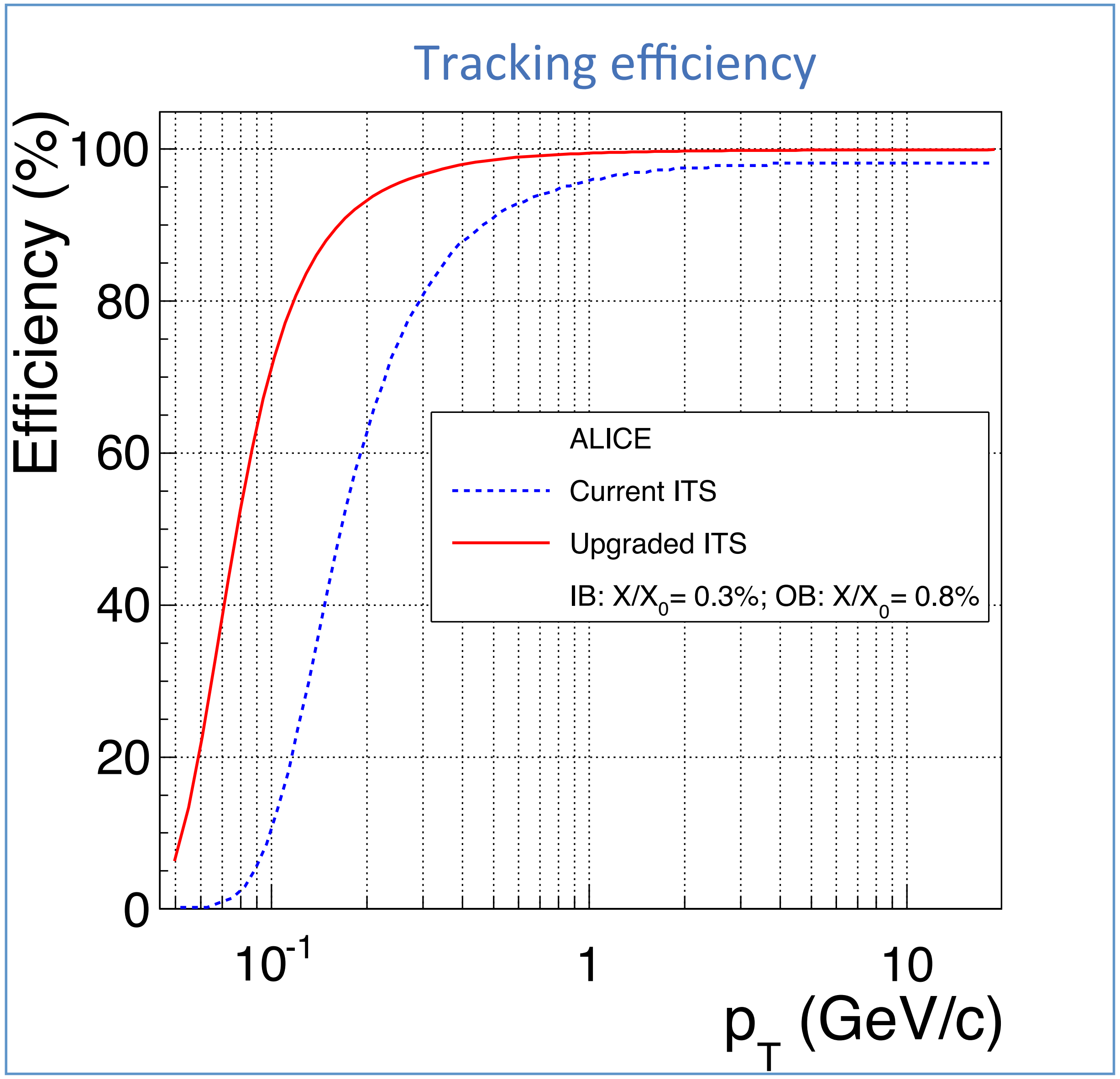
many slides borrowed with credit to L. Musa

ITS Motivation

Impact parameter resolution



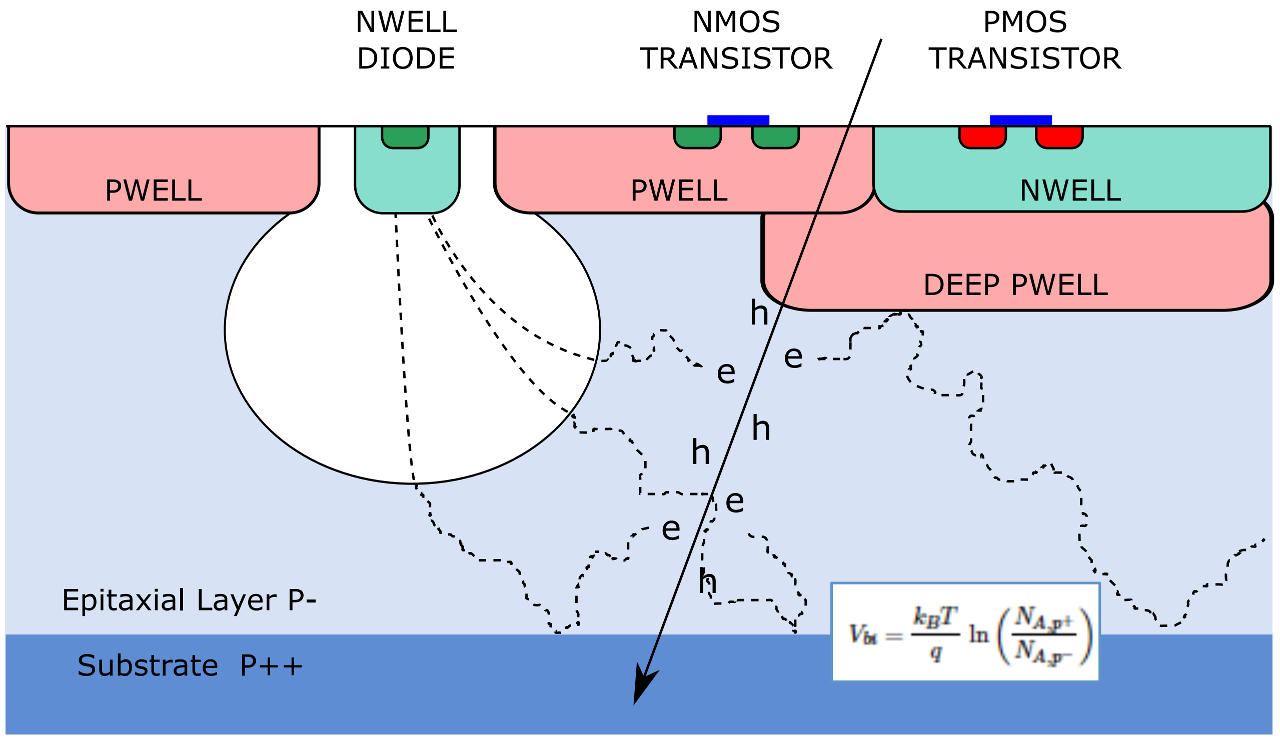
Tracking efficiency (ITS standalone)



~40 μm at p_T = 500 MeV/c

ALPIDE pixel technology

CMOS Pixel Sensor using TowerJazz 0.18μm CMOS Imaging Process



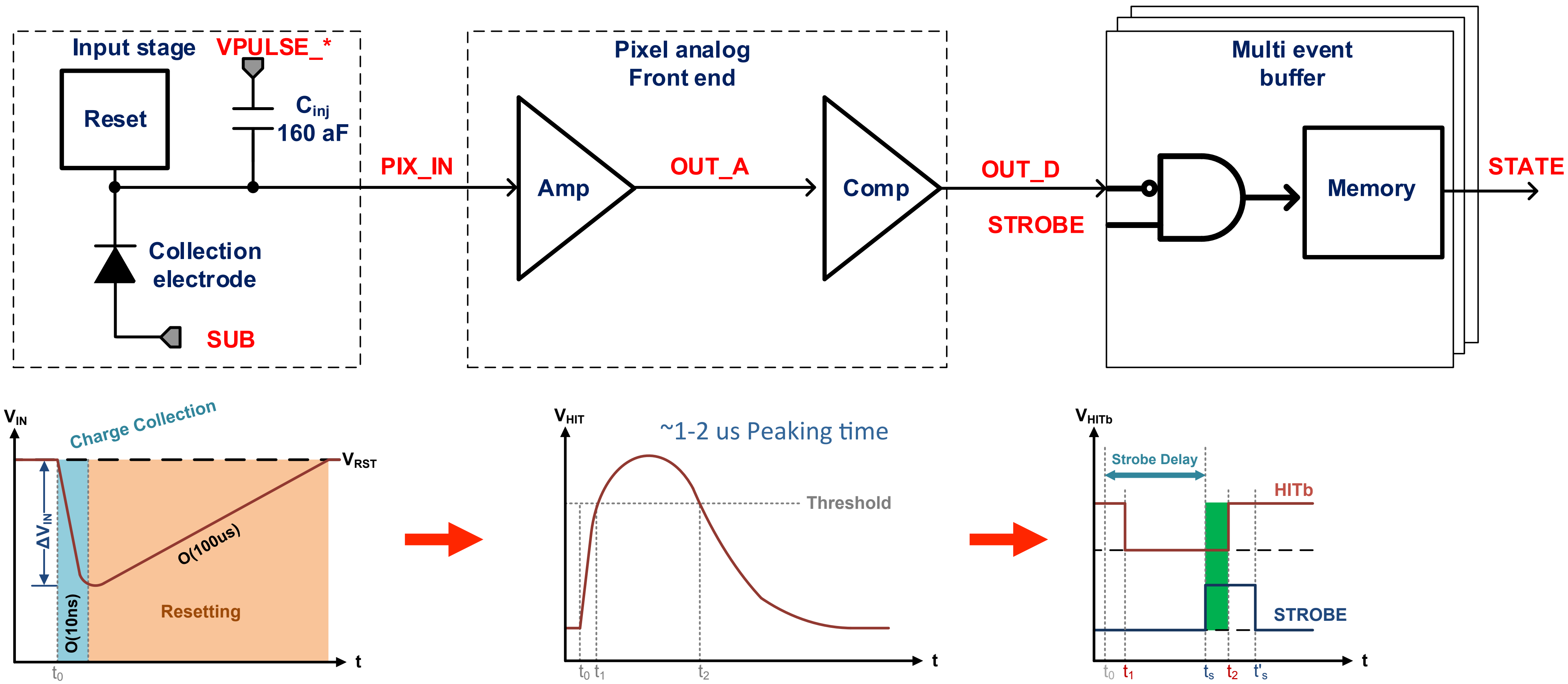
Tower Jazz 0.18 μm CMOS

- feature size 180 nm
- metal layers 6
- gate oxide 3nm

substrate: $N_A \sim 10^{18}$
epitaxial layer: $N_A \sim 10^{13}$
deep p-well: $N_A \sim 10^{16}$

- High-resistivity (> 1kΩ cm) p-type epitaxial layer (18μm to 30μm) on p-type substrate
- Small n-well diode (2 μm diameter), ~100 times smaller than pixel => low capacitance
- Application of (moderate) reverse bias voltage to substrate (contact from the top) can be used to increase depletion zone around NWELL collection diode
- Deep PWELL shields NWELL of PMOS transistors to allow for full CMOS circuitry within active area

ALPIDE Operation

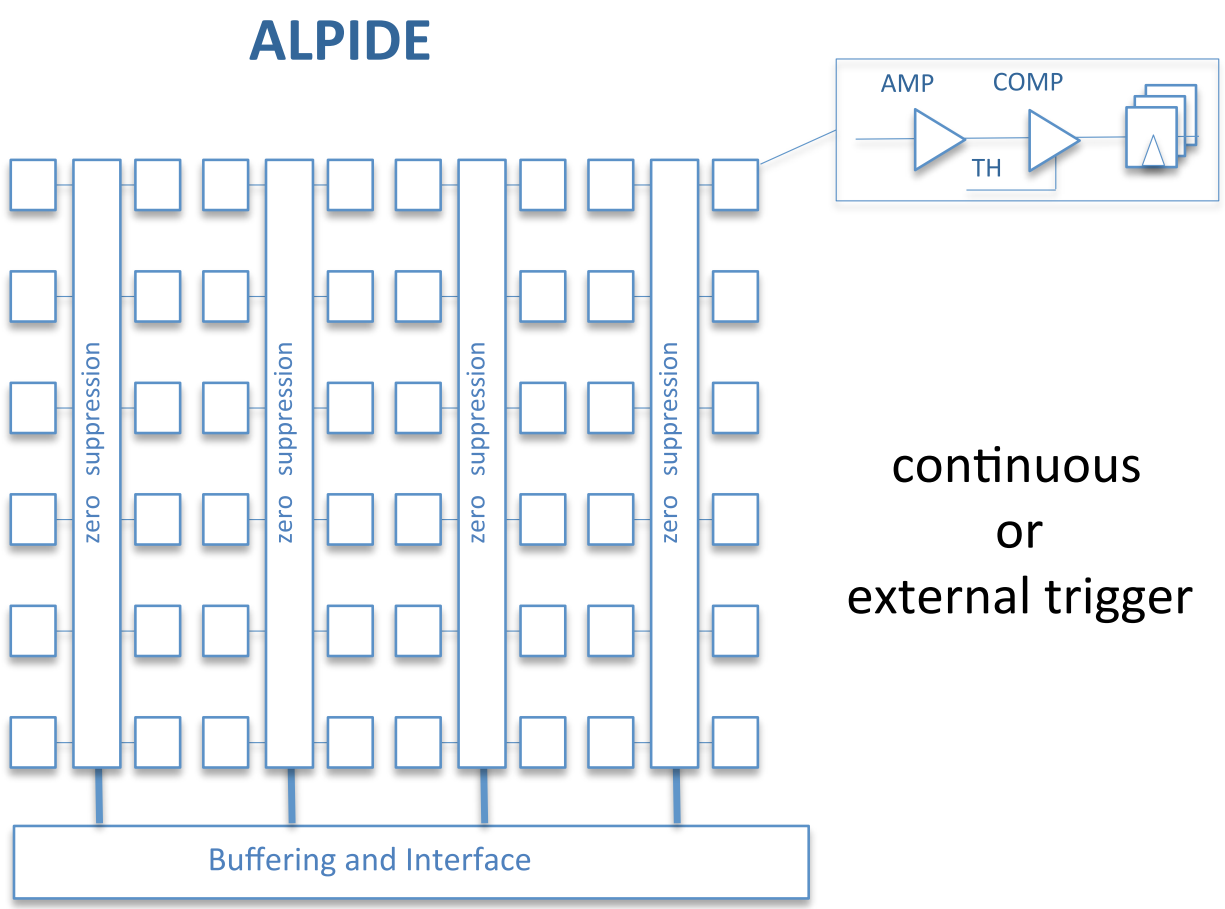


ultra low-power front-end circuit
40nW / pixel

Front-end acts as delay line

- Sensor and front-end continuously active
- Upon particle hit front-end forms a pulse with ~1-2μs peaking time
- Threshold is applied to form binary pulse
- Hit is latched into a (3-bit) memory if strobe is applied during binary pulse

ALPIDE Readout



continuous
or
external trigger

Architecture

- In-pixel amplification
- In-pixel discrimination
- In-pixel (multi-) hit buffer
- In-matrix sparsification

Key Features

- 28 μm x 28 mm pixel pitch
- Continuously active, ultra-low power front-end (40nW/pixel)
- No clock propagation to the matrix ➔ ultra-low power matrix readout (2mW whole chip)
- Global shutter (<10μs): triggered acquisition or continuous

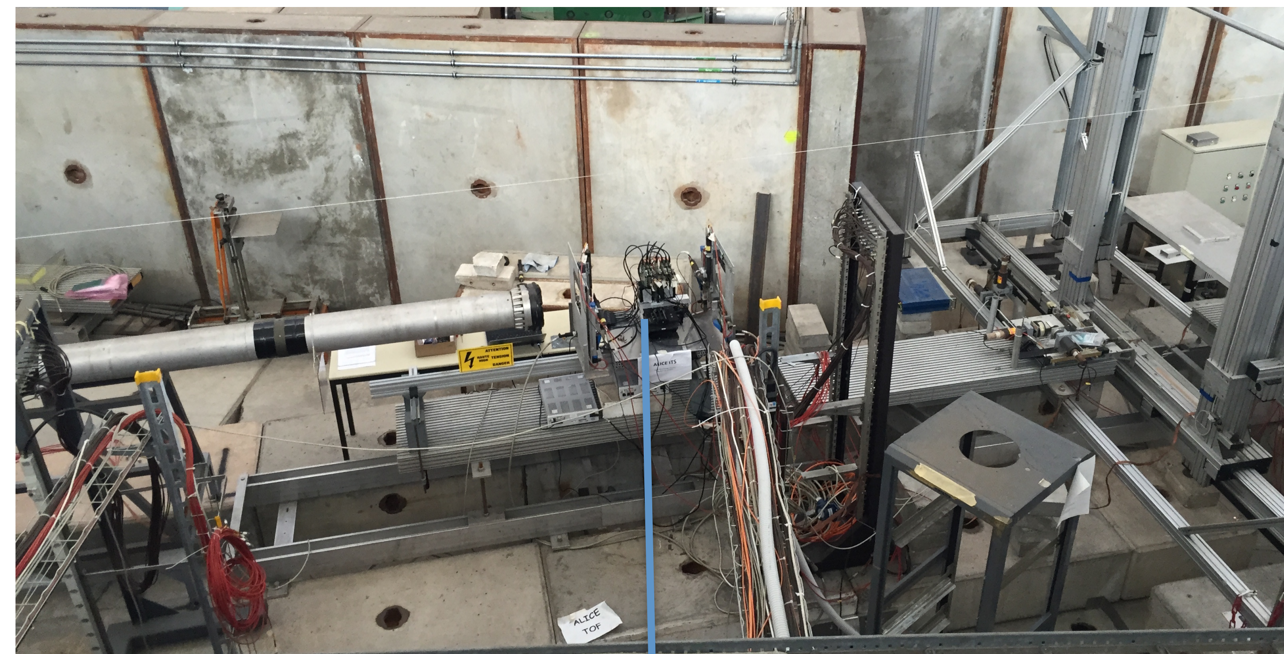
CERN Test Beam

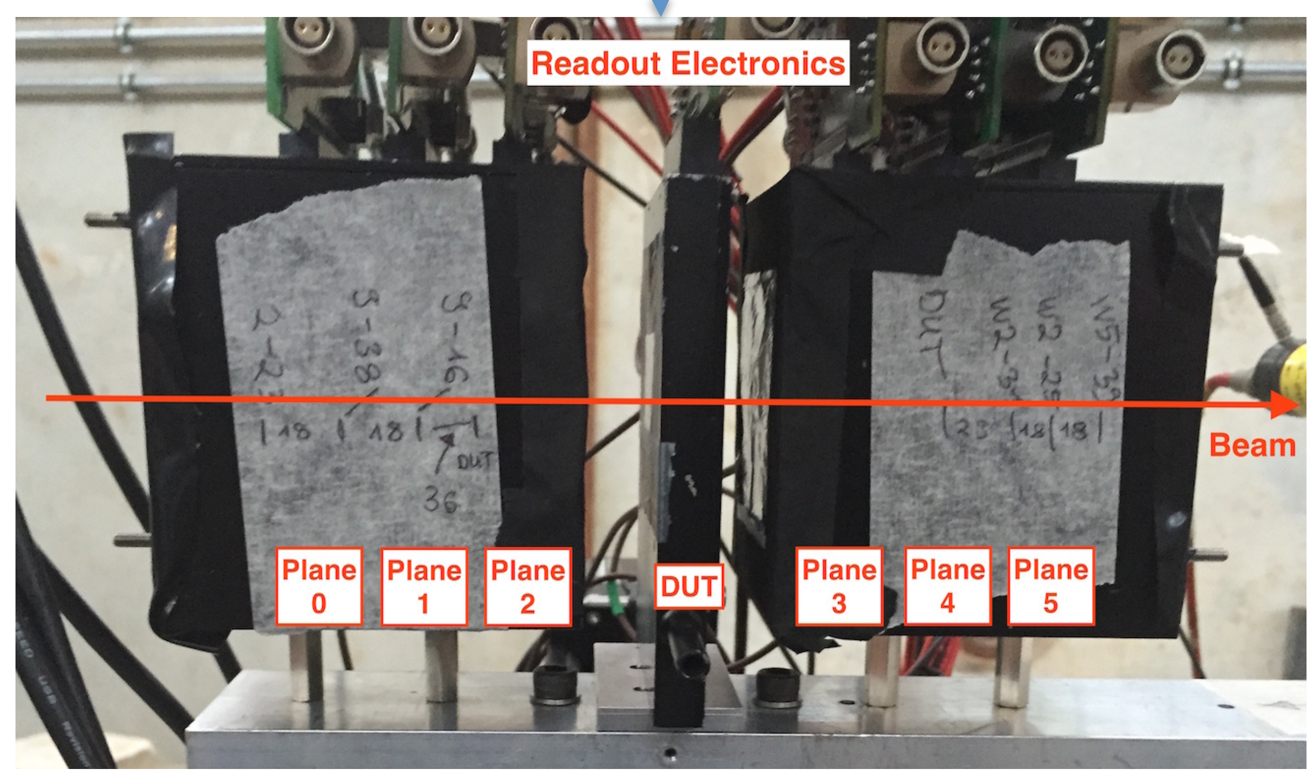
Test Beam Set-up

- 6 GeV/c π^- beam at CERN PS
- 6 reference planes based on pALPIDE-1
- Single pALPIDE-2 as Device Under Test (DUT) in the center
- Track resolution of about 2.8μm (<< 28μm)

Analysis Method

- Extrapolate track from referecne planes trough DUT
- Search for clusters next to extrapolated impinging point → detection efficiency
- Obtain **cluster size**
- Compare extrapolated and actual position → **position resolution**

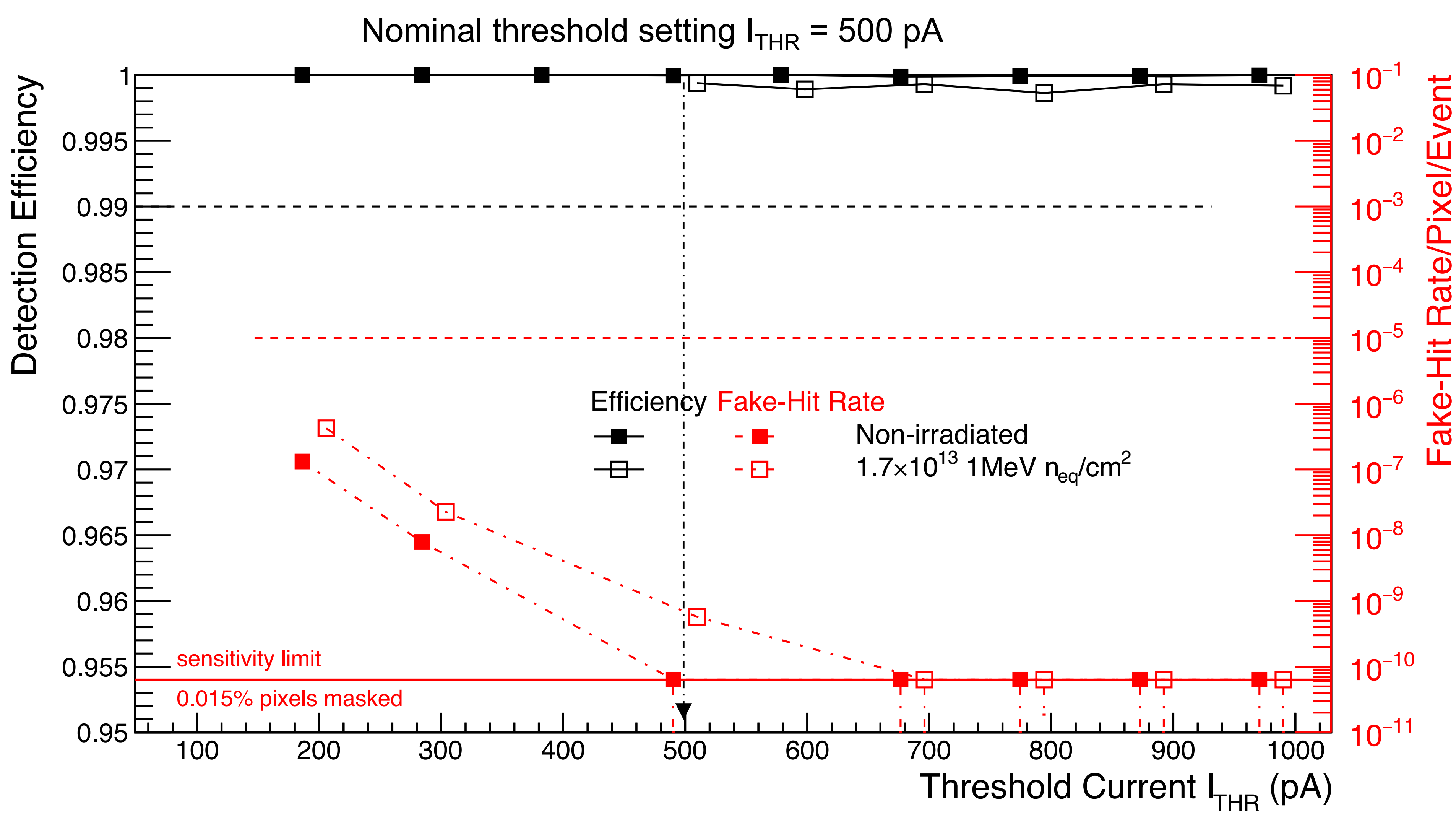




ALICE Test Beam Data

Efficiency and fake hit rate

epi=30μm, V_{BB}=-6V, spacing=4μm



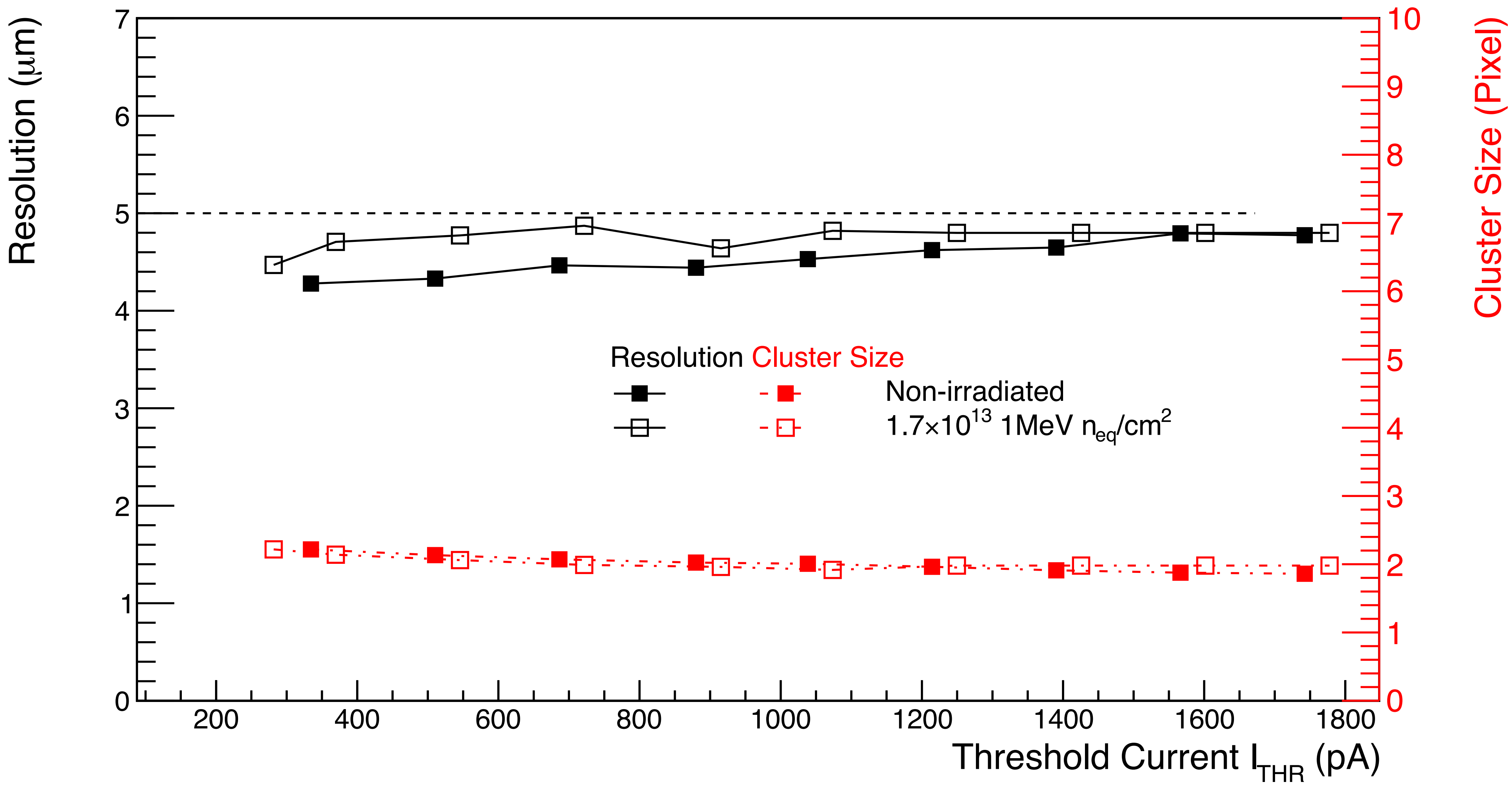
Even larger operation margin for 30μm epi layer and 4μm spacing

- Results refer to chips with 30μm high-res epi layer, thinned to 50 μm: 1 non irradiated and 1 irradiated with 10^{13} 1MeV n_{eq} / cm^2

ALICE Test Beam Data #2

Spatial Resolution and Cluster Size

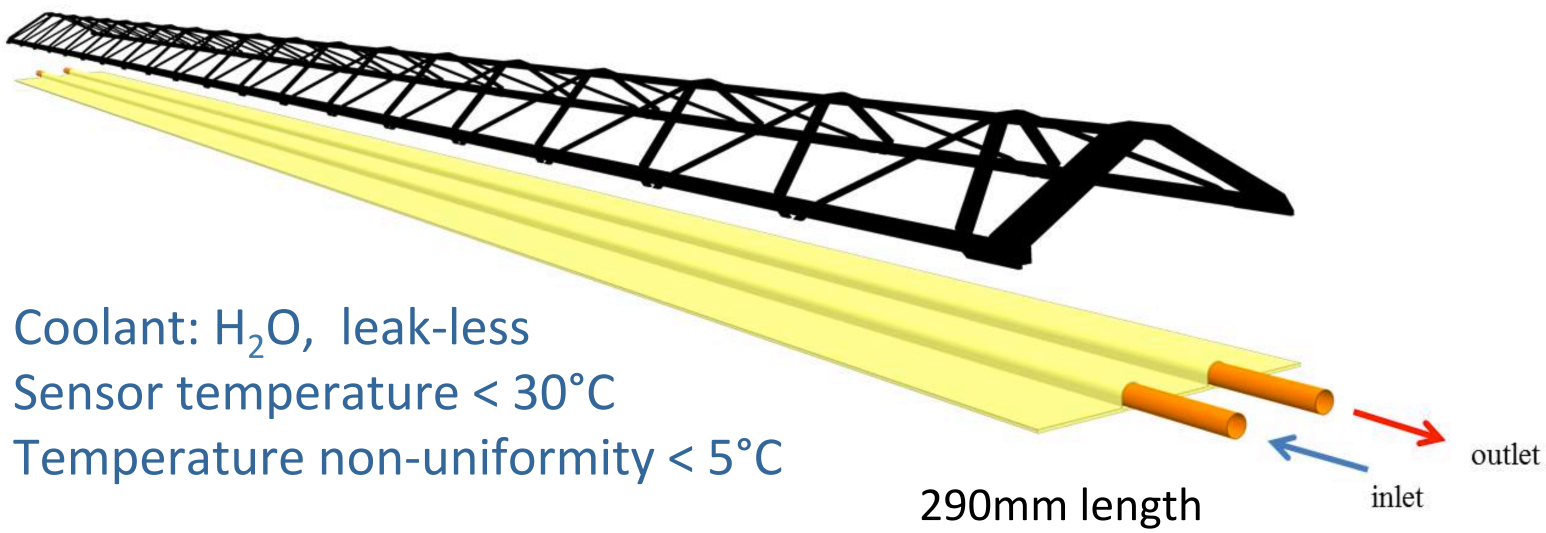
epi=30μm, V_{BB}=-6V, spacing=4μm



σ_{det} ≈ 5 μm is achieved before and after irradiation

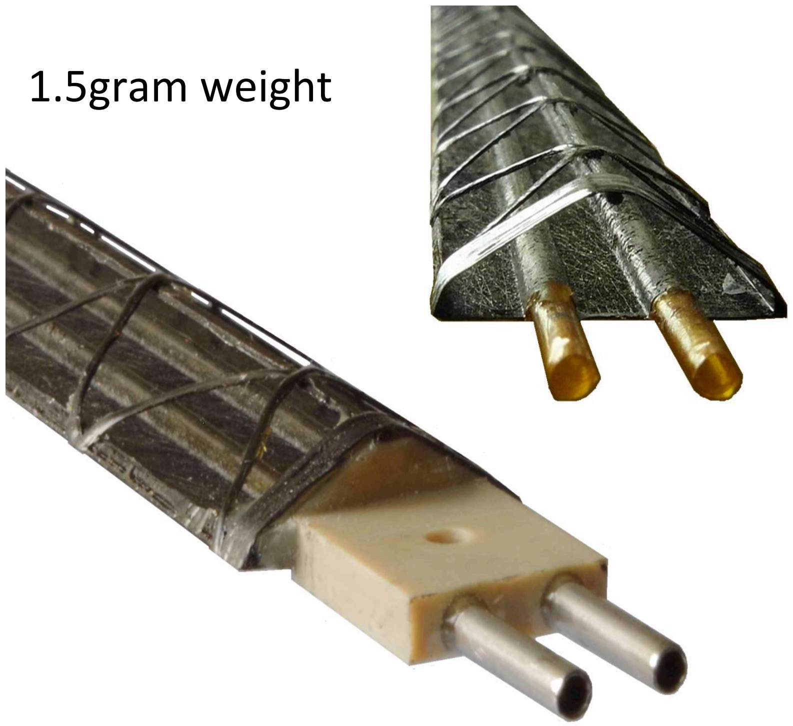
- Results refer to chips with 30μm high-res epi layer, thinned to 50 μm
  1 non irradiated and 1 irradiated with $1.7\text{x}10^{13}$ 1MeV n_{eq} / cm^2

Inner Barrel Staves



Coolant: H_2O, leak-less
Sensor temperature < 30°C
Temperature non-uniformity < 5°C

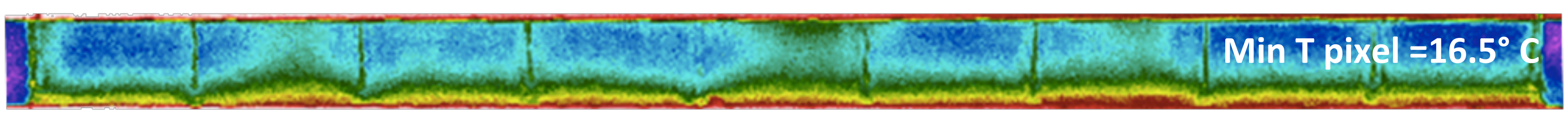
1.5gram weight



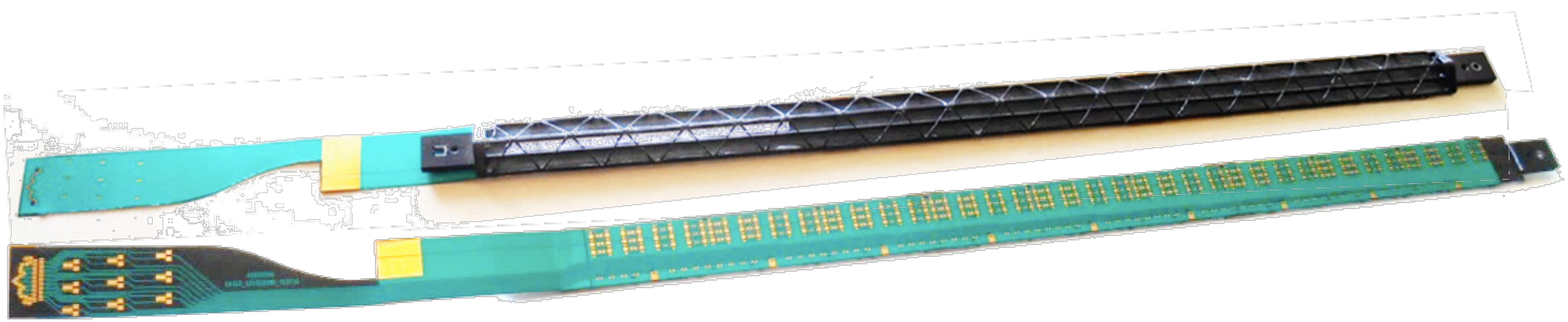
W = 100 mW / cm^2 (> x2 nominal) , H_2O flow rate = 3 Lh^{-1}

Tin=15.8° C

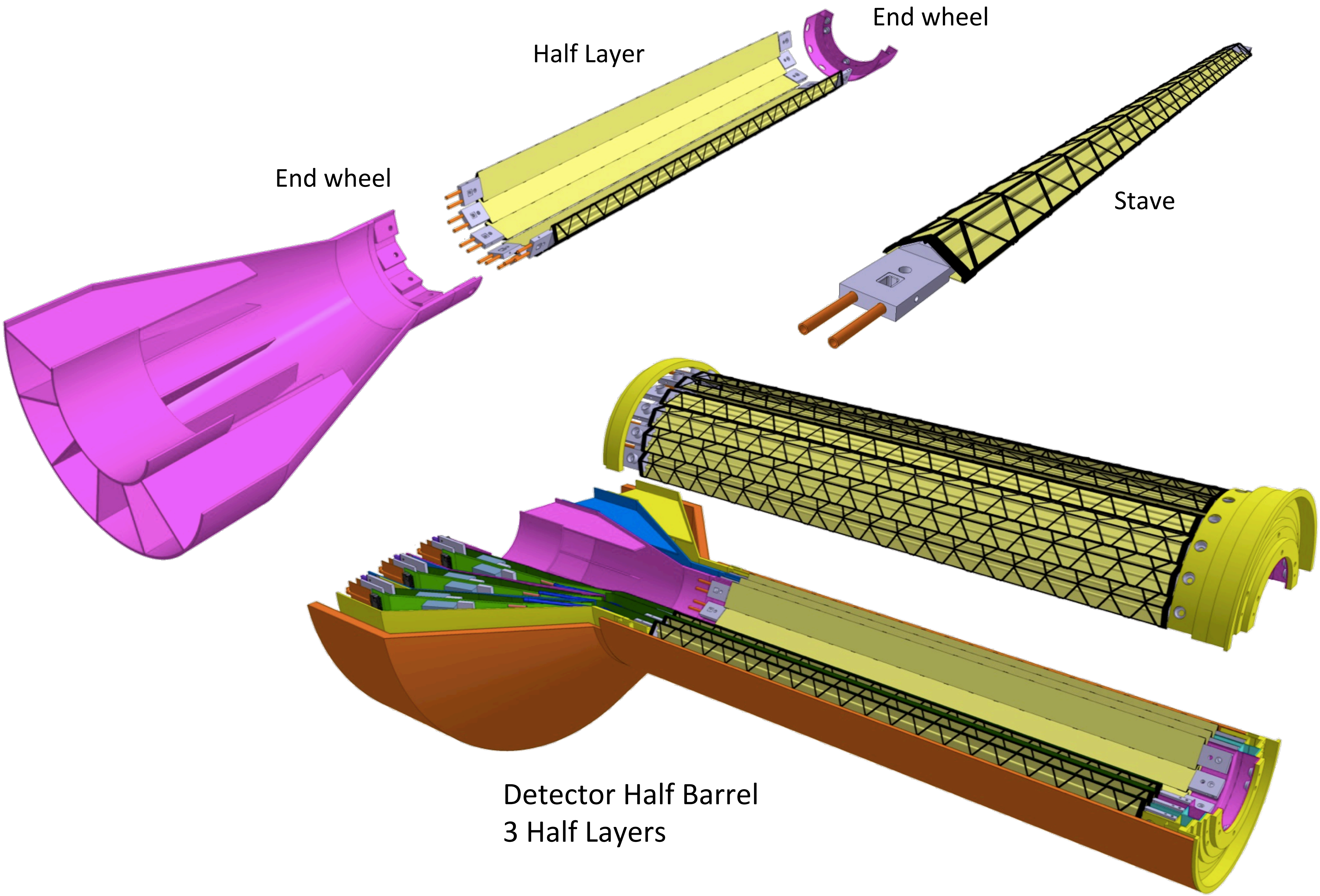
Tout=16.6 °C



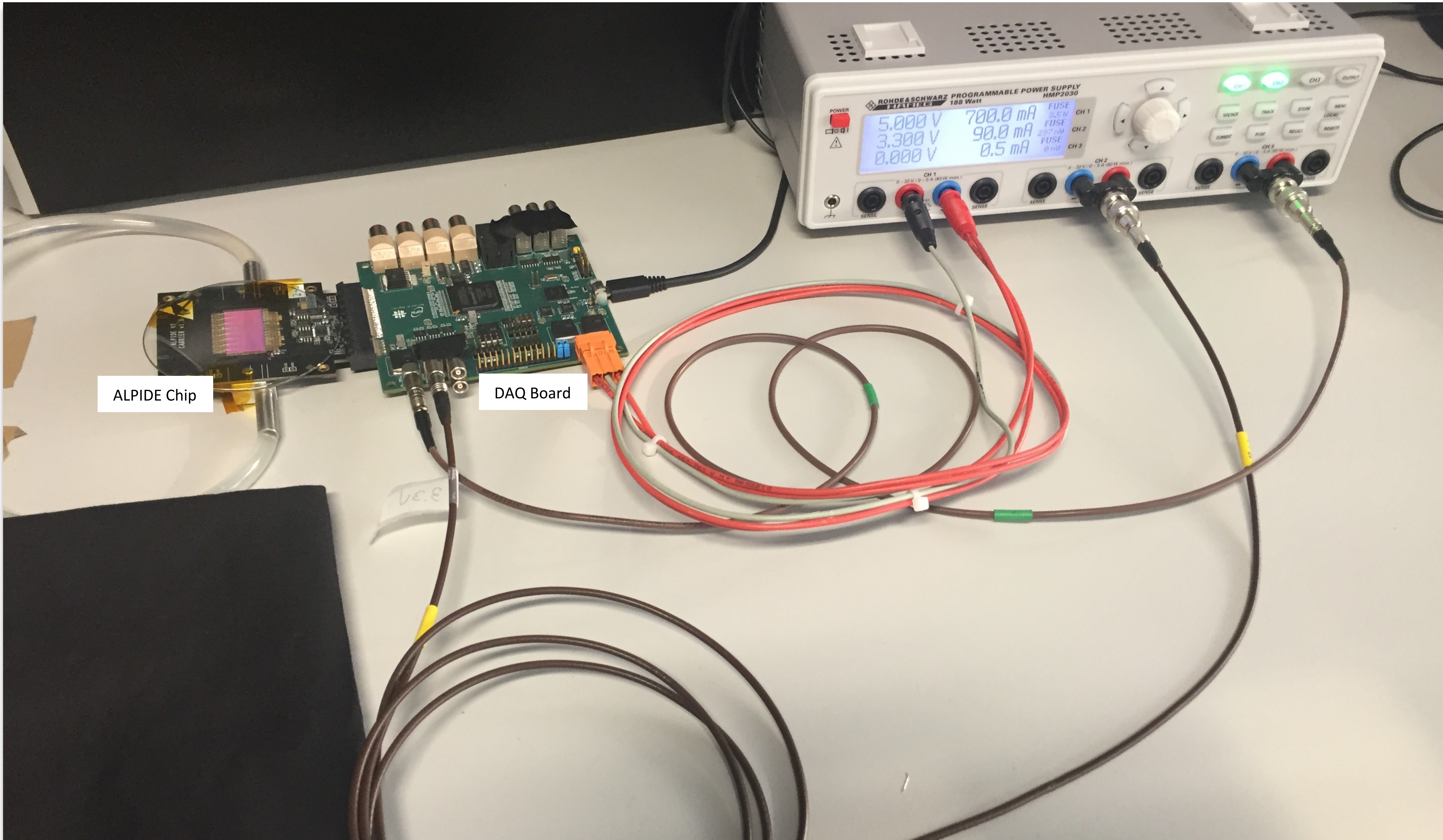
Max T periph=18.5° C



ALICE Inner Barrel Support & Services

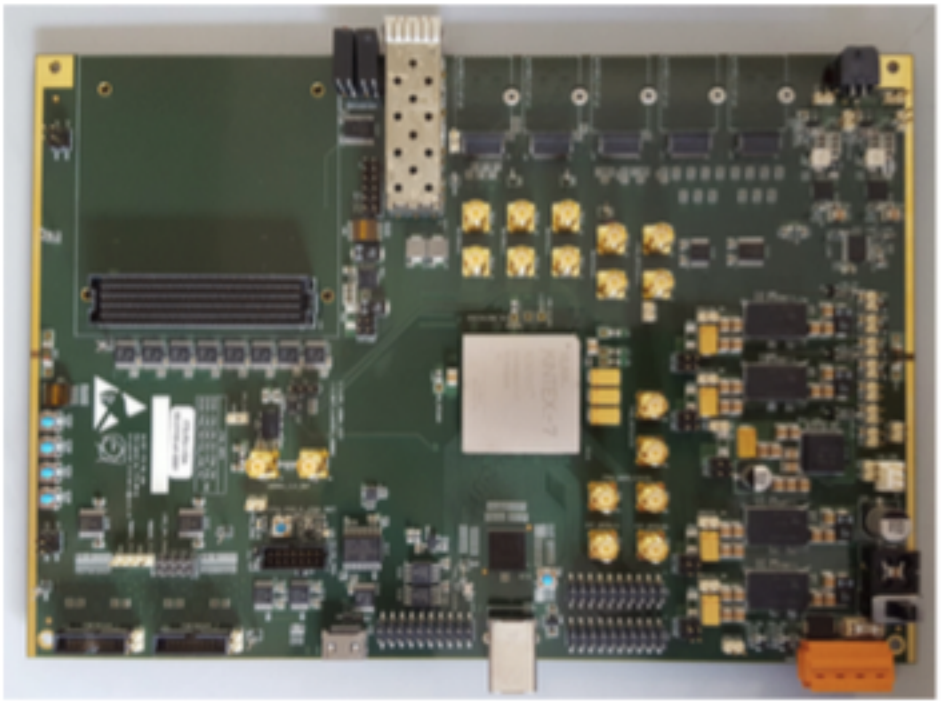


Detector Prototyping



Detector Prototyping

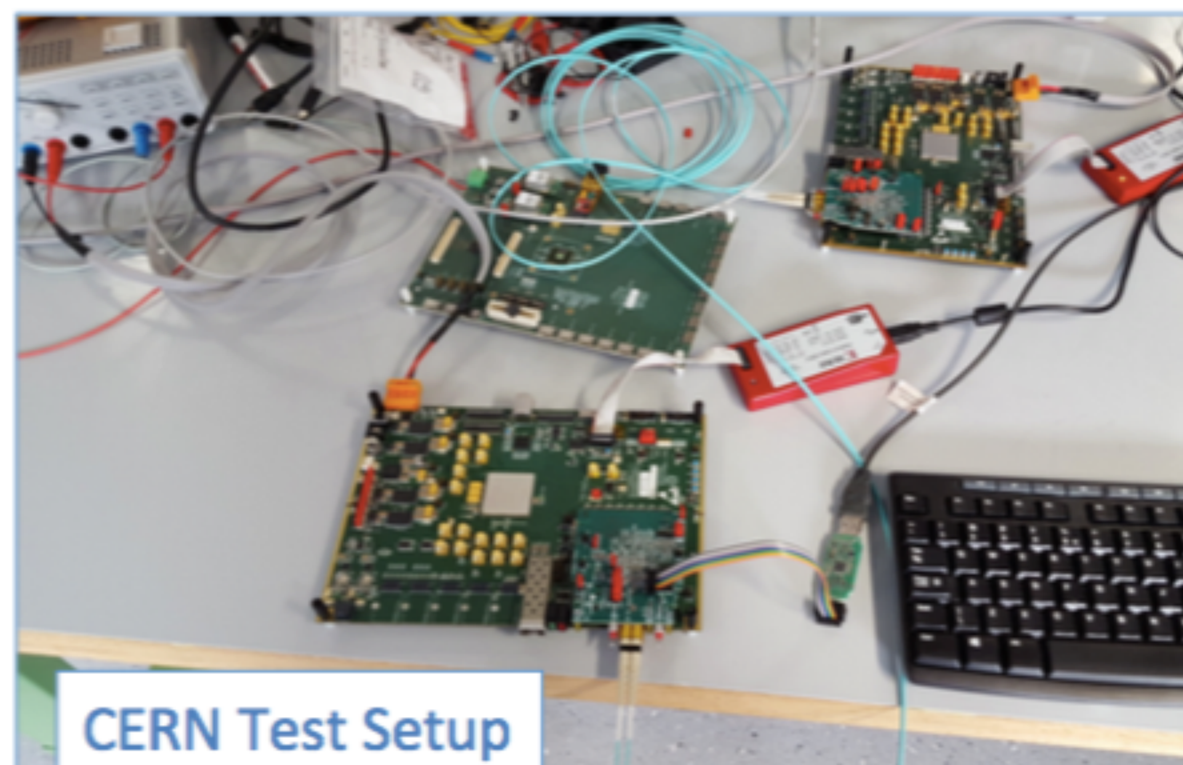
Readout Unit Prototype Version 0a ("RUv0a")



GBT FMC Mezzanine ("GBTxFMC")
Readout Unit Daughter Board

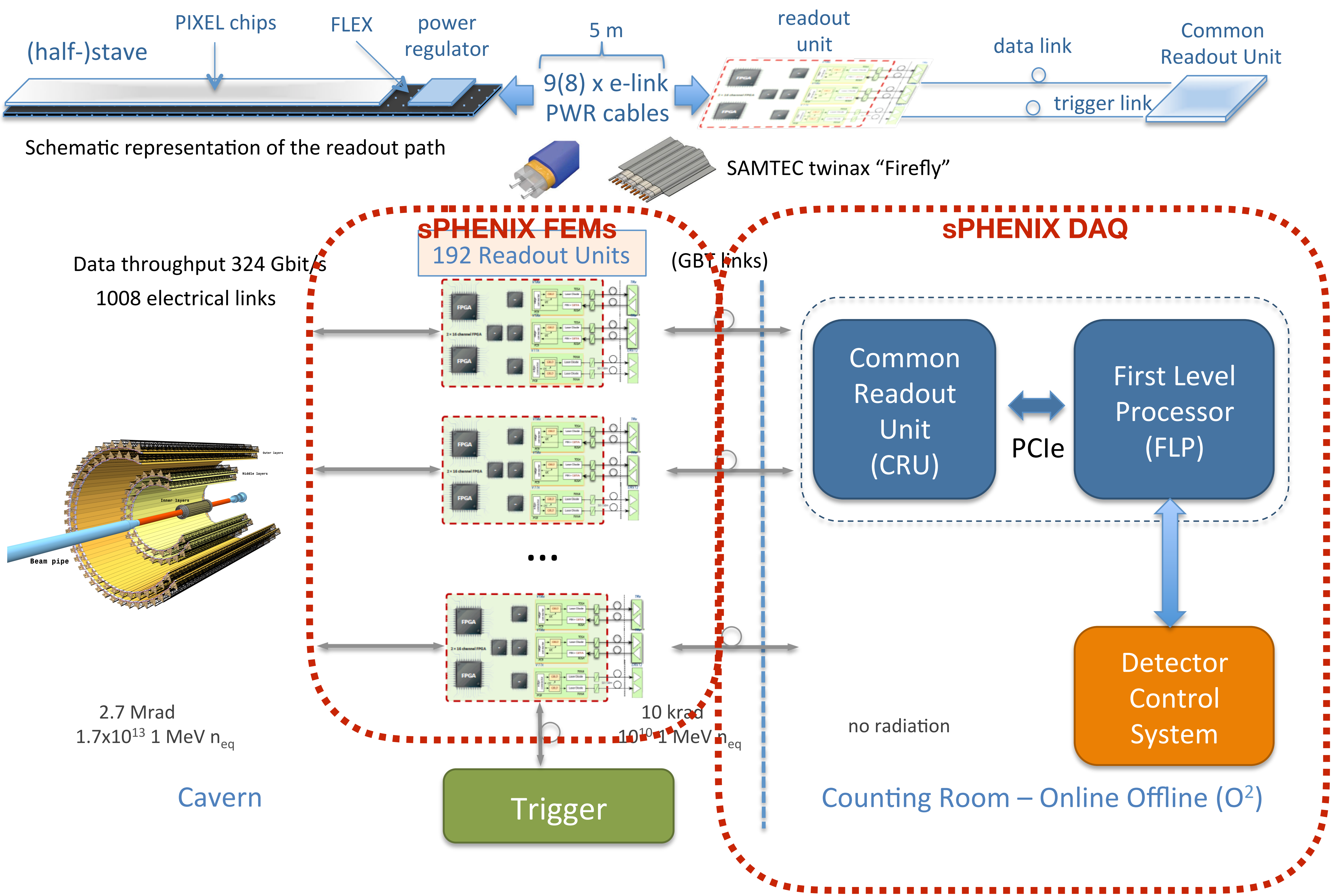
First Functional Prototype of Readout Electronics is available

- All interfaces are working
- Firmware development has started



CERN Test Setup

Readout Scheme



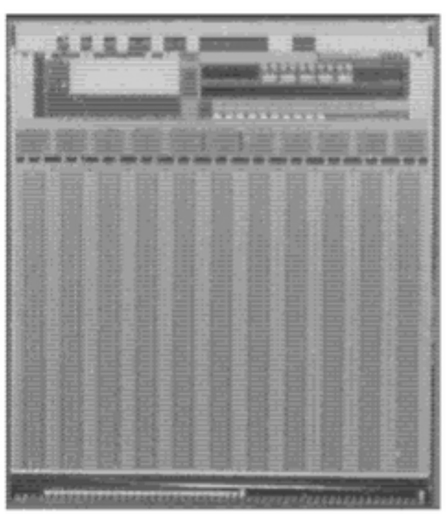
LANL LDRD Deliverables

Our primary experimental goal for the LDRD process is a small-coverage 3-layer prototype tracker with MAPS-based sensor arrays.

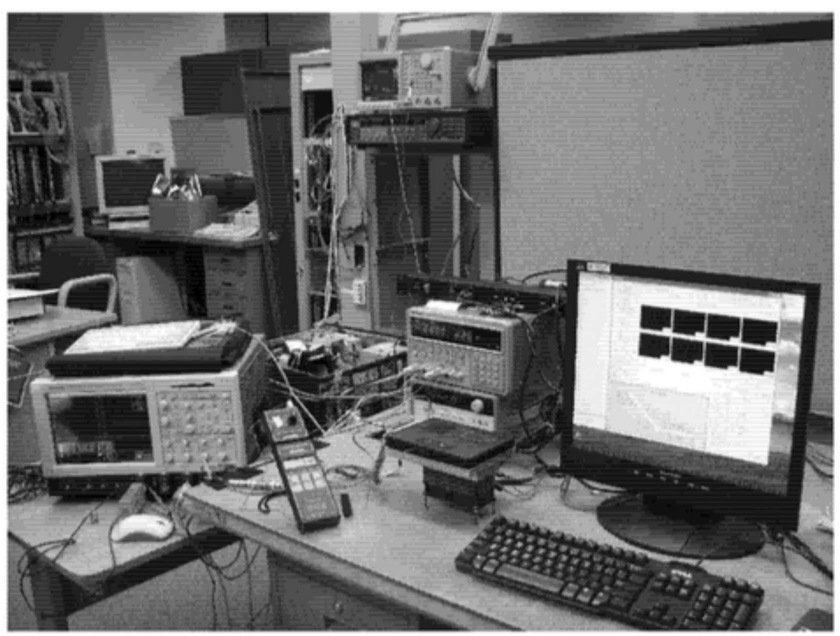
Purpose: garner experience with MAPS, finalize the technical design and readout electronics for sPHENIX.

Prepare fully for final construction activities.

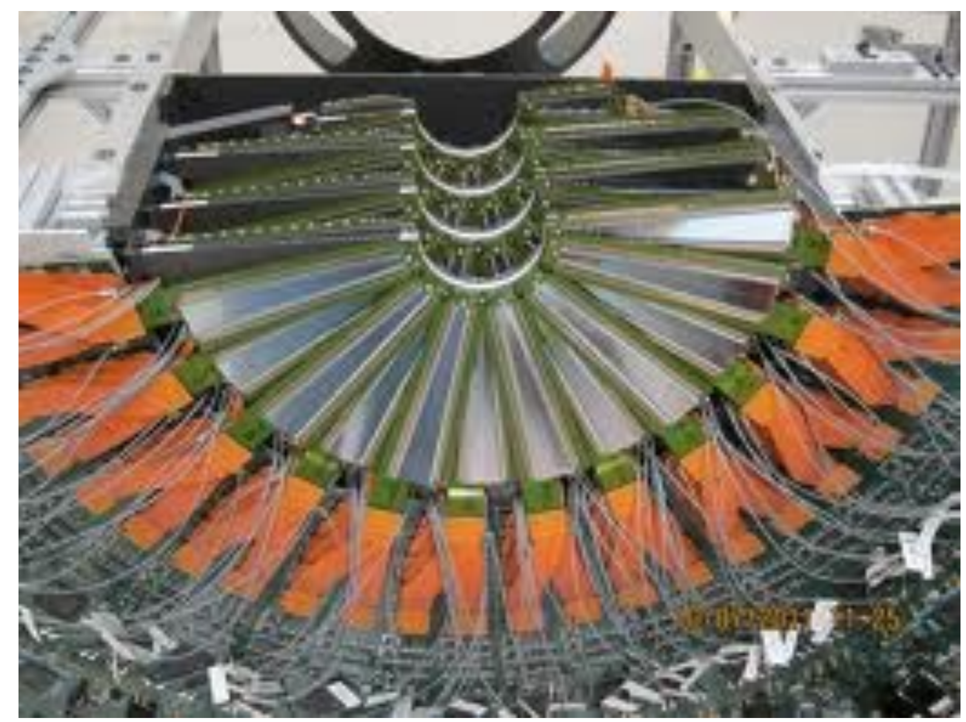
prototyping under LDRD:



prototype pixel sensor



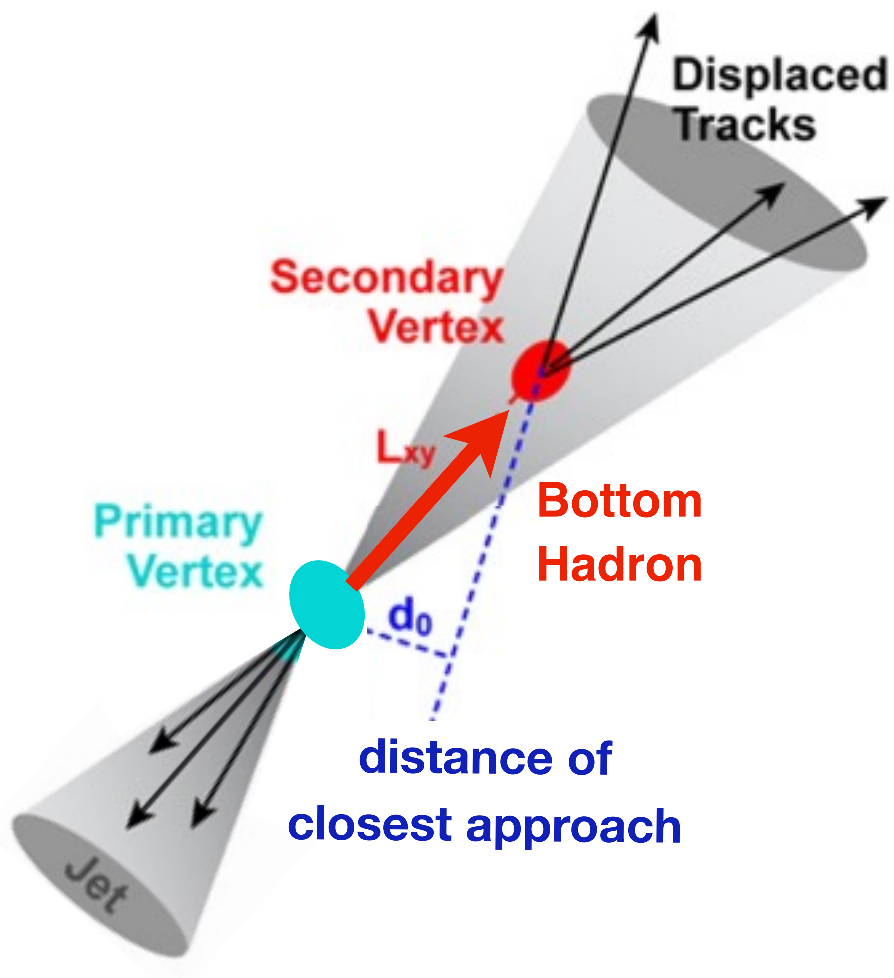
final tracker support after LDRD:



this is a proven successful strategy

Our proposal was well received and we were invited to expand the scope and resubmit. We were also highly ranked in this years annual LDRD priorities.

Summary

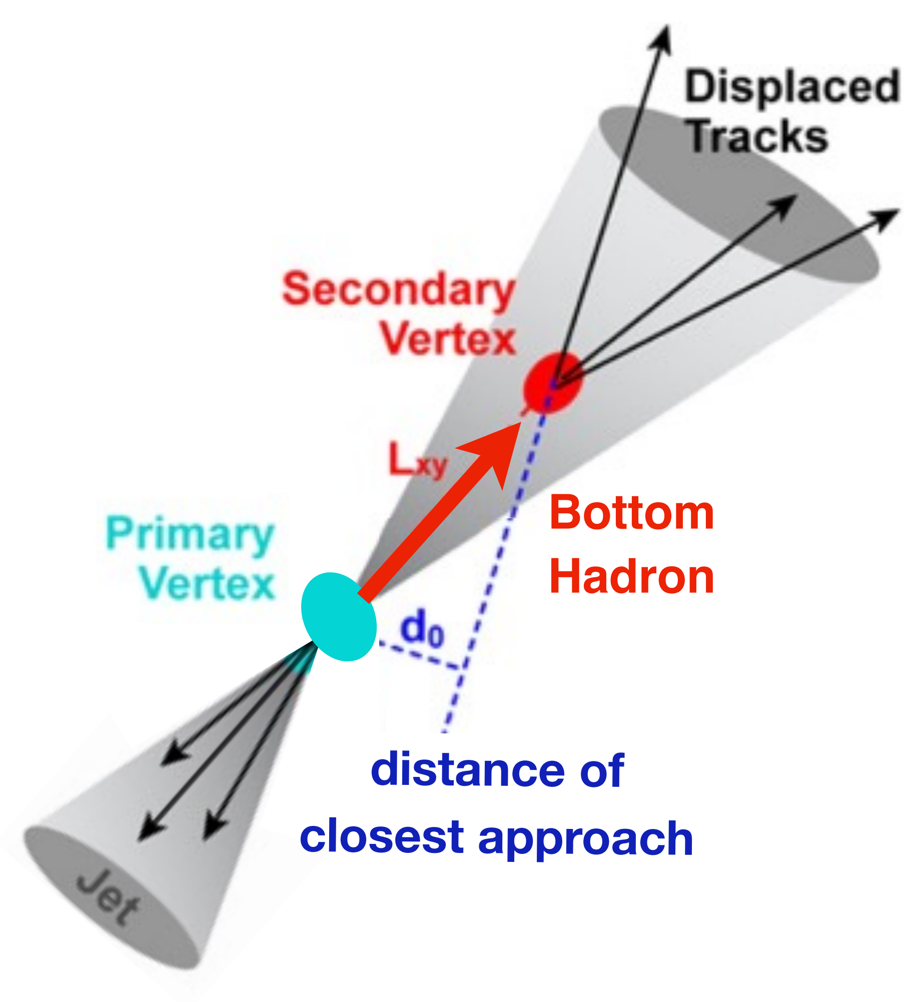


Most viable approaches to **bottom identification**: track counting and 2nd vertexing both **require highly efficiency tracking**.

R&D from the LHC upgrades has improved greatly on pixel dimensions (important for 2nd vertexing) and efficiency.

sPHENIX should greatly benefit from these developments, to ignore them will imperil our physics output.

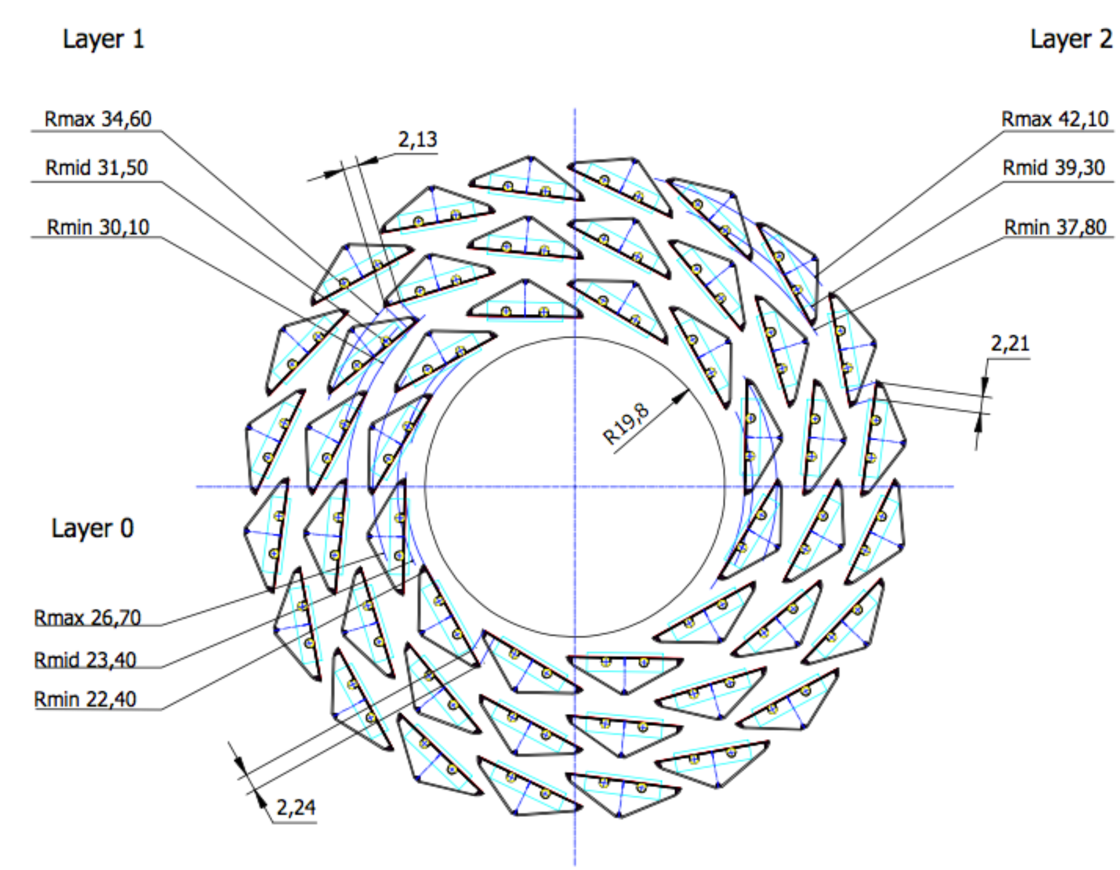
Summary



Most viable approaches to **bottom identification**: track counting and 2nd vertexing both **require highly efficiency tracking**.

R&D from the LHC upgrades has improved greatly on pixel dimensions (important for 2nd vertexing) and efficiency.

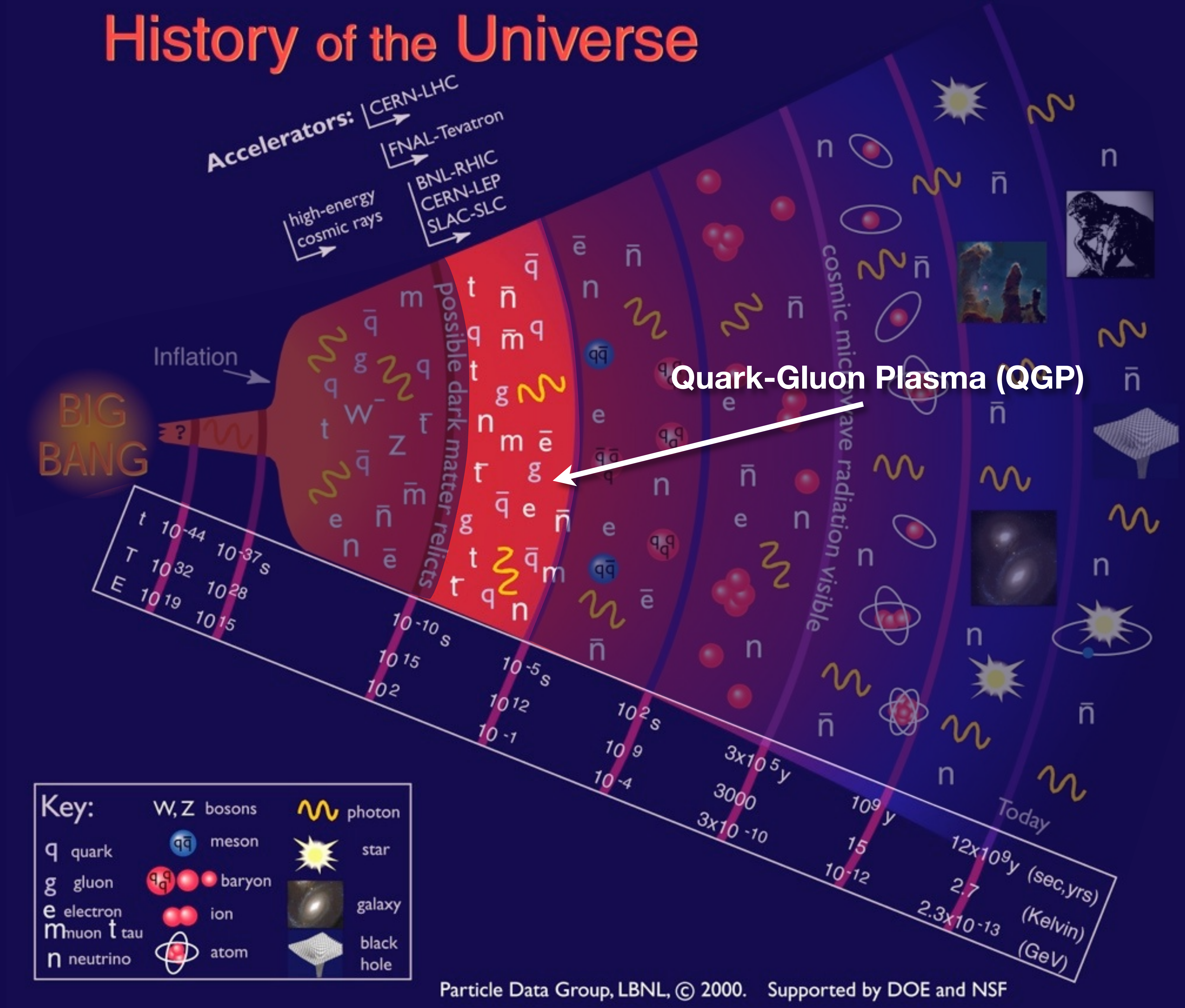
sPHENIX should greatly benefit from these developments, to ignore them will imperil our physics output.



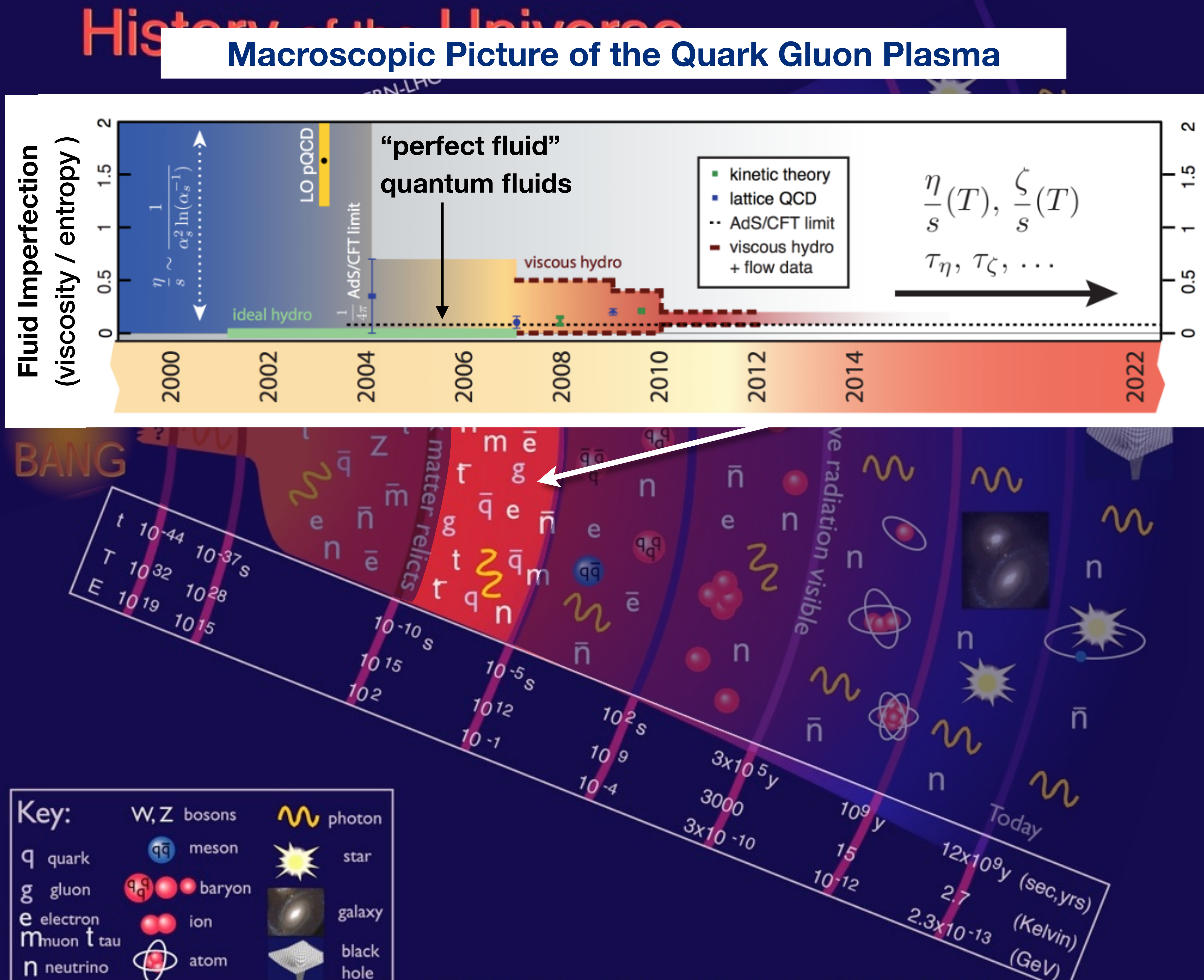
A new set of innermost tracking layers will ensure that heavy flavor jets remain the 3rd pillar of the sPHENIX program.

Thank you!

Backup Slides


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
Quark-Gluon Plasma (QGP)
t 10-44 10-37 s
T 1032 1028
E 1019 1015
10-10 s
1015
102
10-5 s
1012
10-1
102 s
109
10-4
3x105 y
3000
3x10-10
109 y
15
10-12
Today
12x109y (sec,yrs)
2.7 (Kelvin)
2.3x10-13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W,Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Macroscopic Picture of the Quark Gluon Plasma



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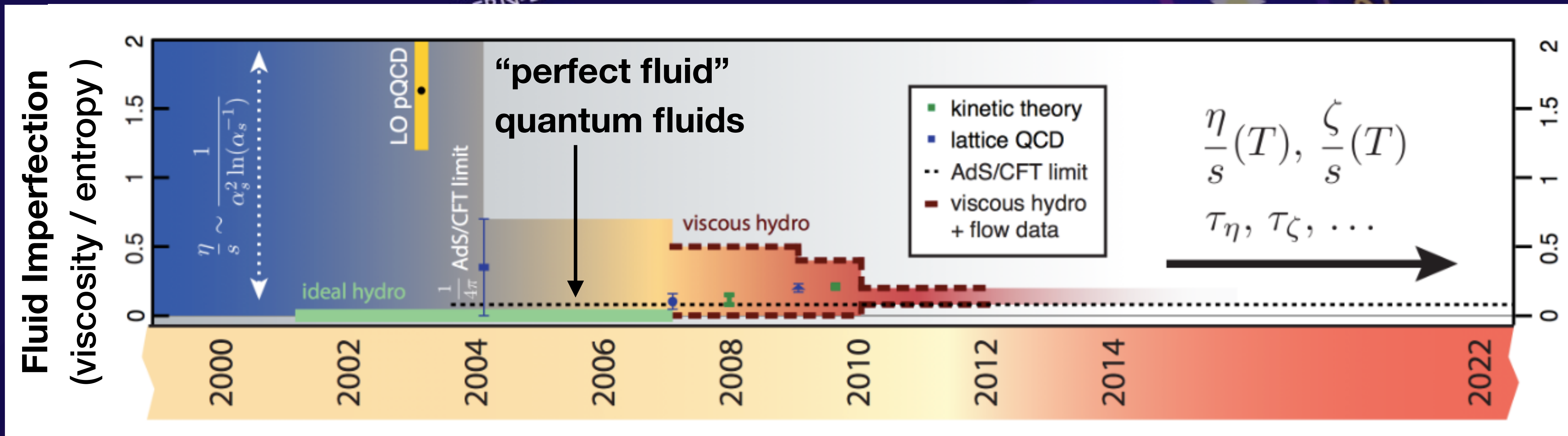
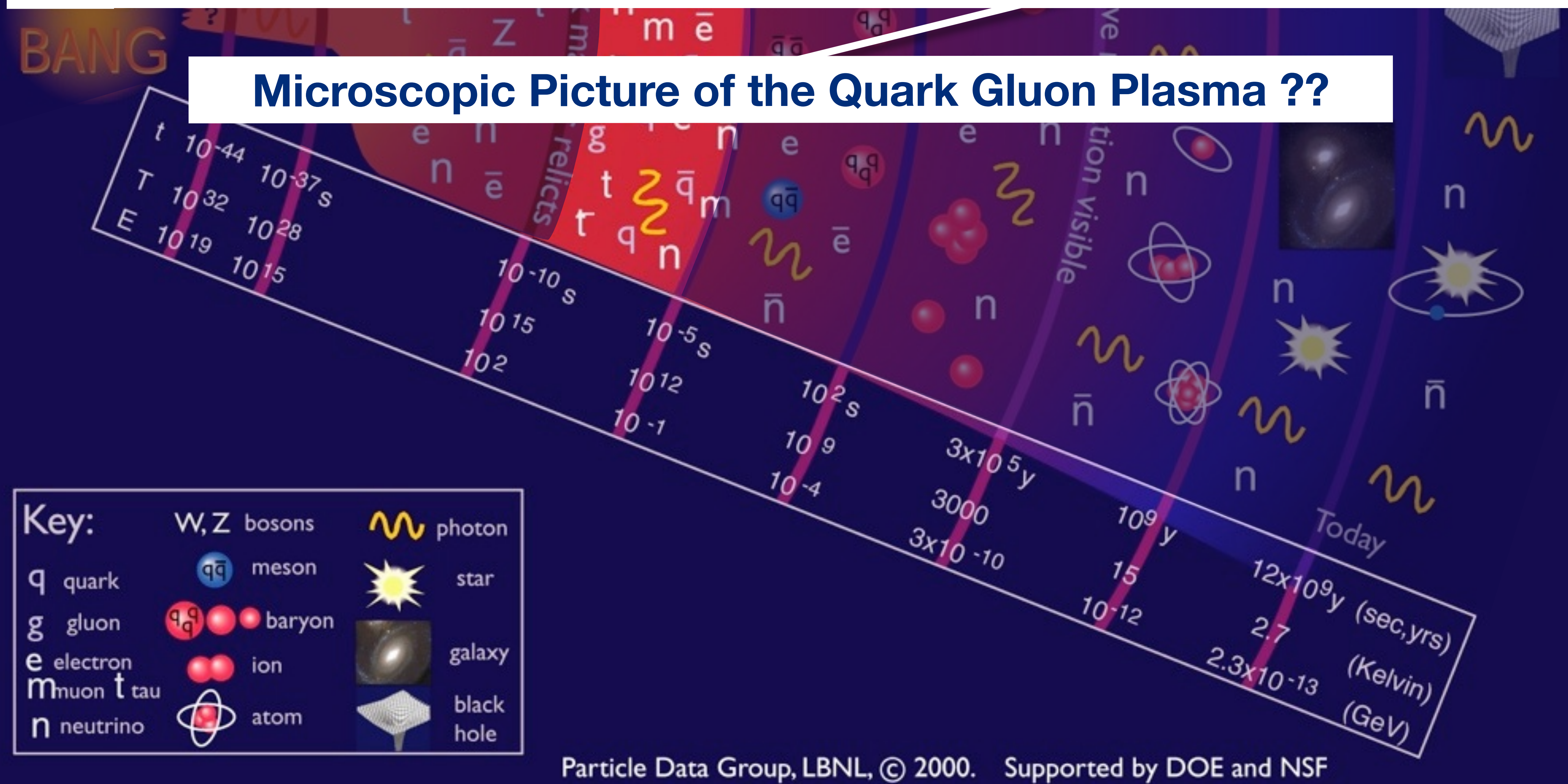
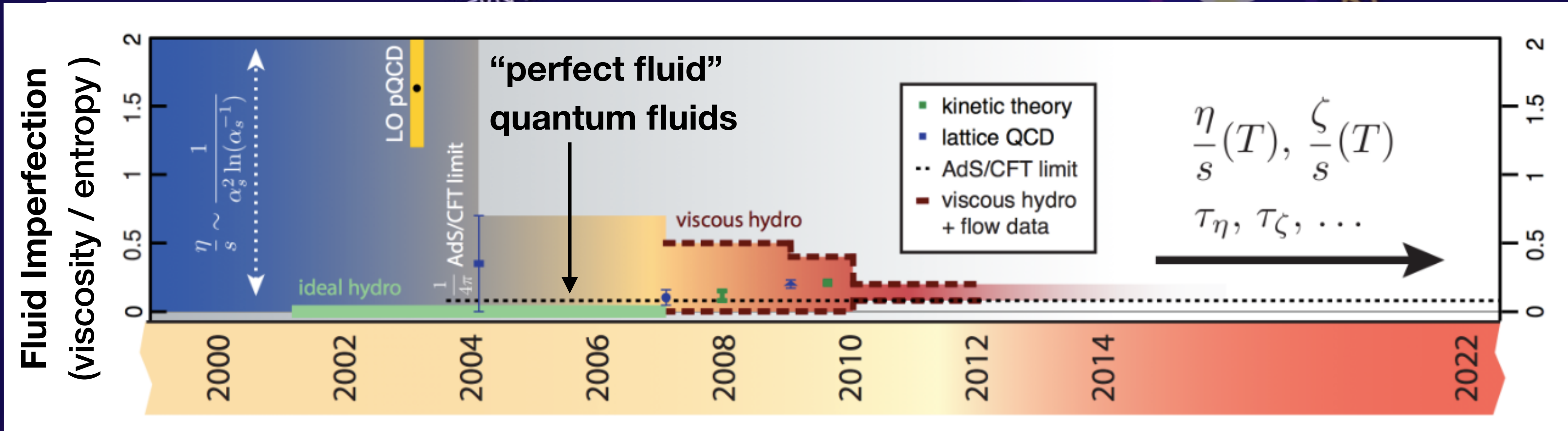


Microscopic Picture of the Quark Gluon Plasma ??

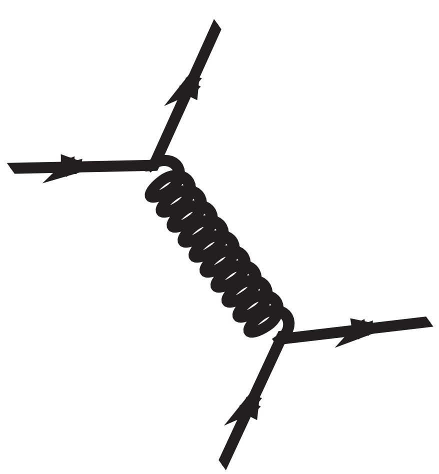


Macroscopic Picture of the Quark Gluon Plasma

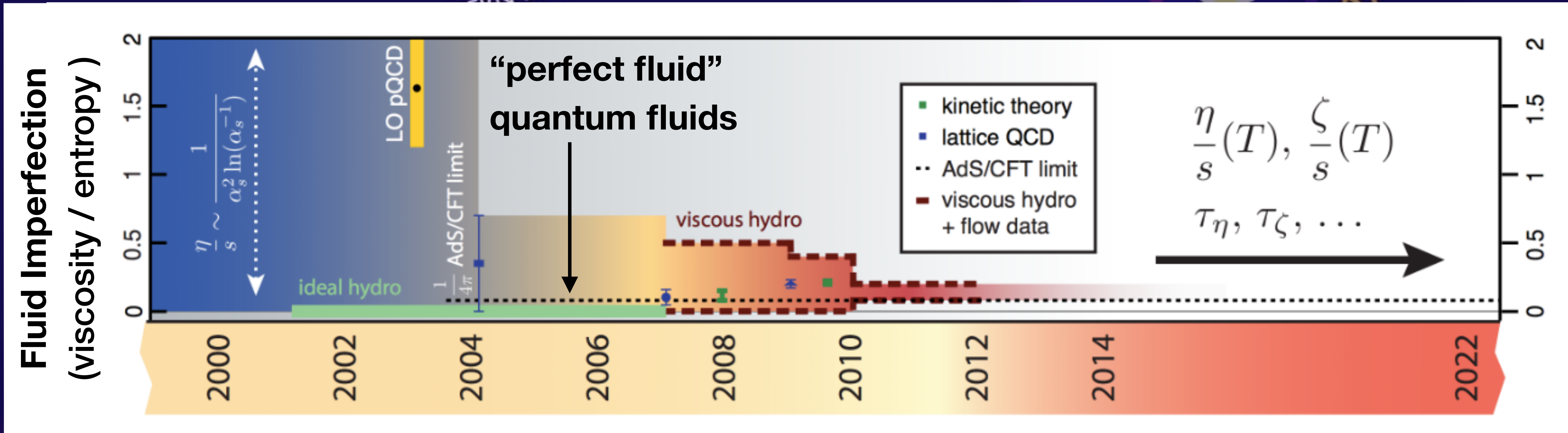


Microscopic Picture of the Quark Gluon Plasma ??

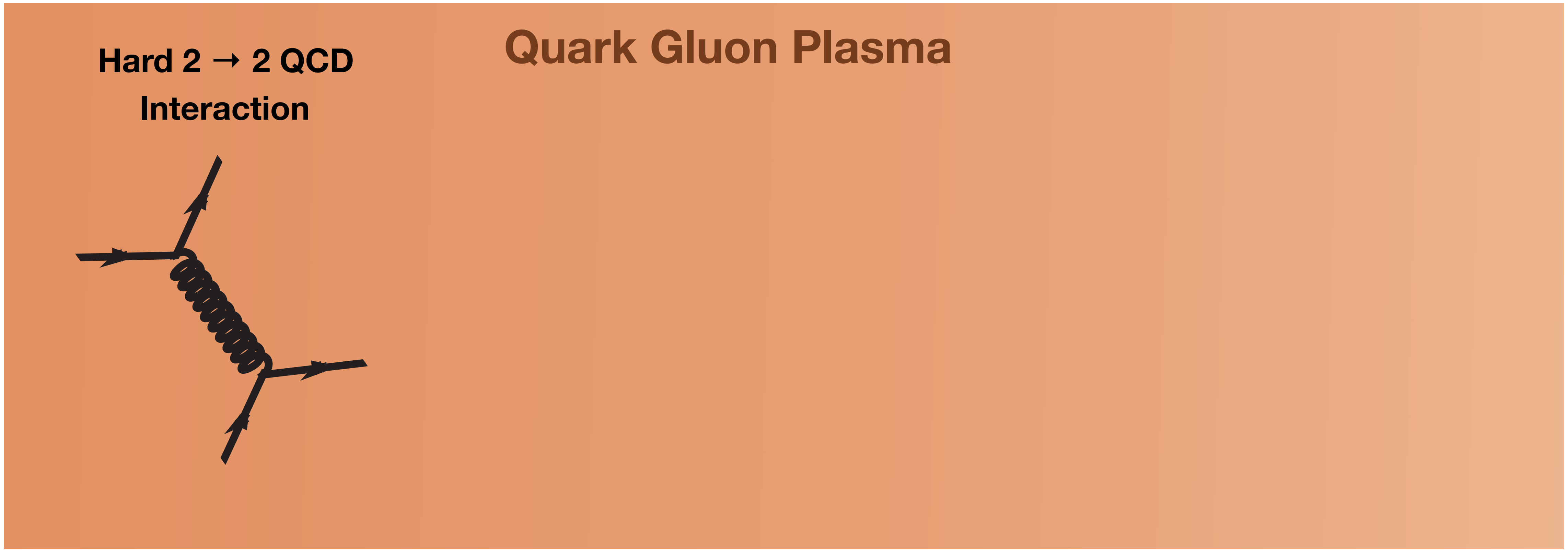
Hard 2 → 2 QCD Interaction



Macroscopic Picture of the Quark Gluon Plasma



Microscopic Picture of the Quark Gluon Plasma ??



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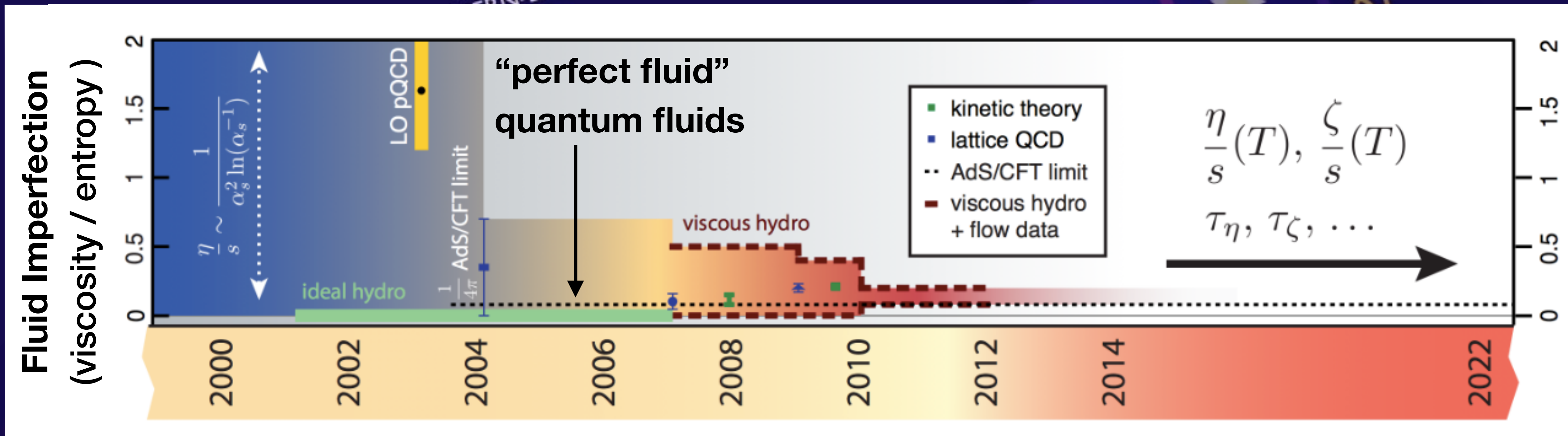

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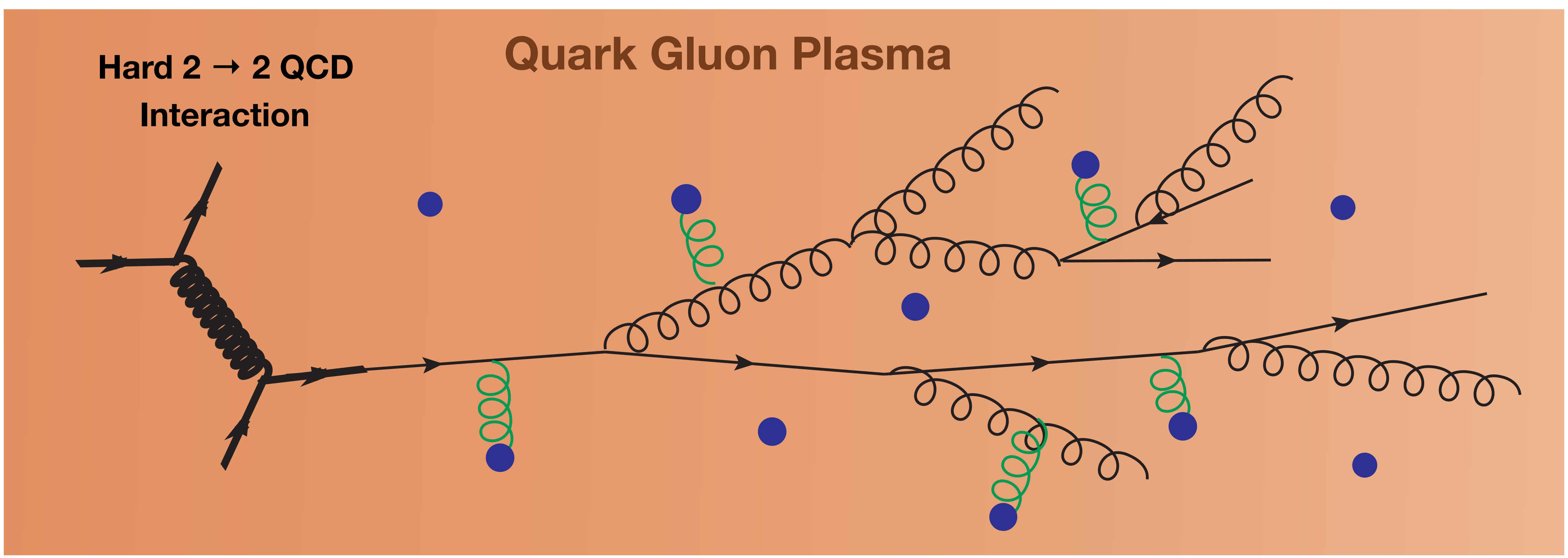

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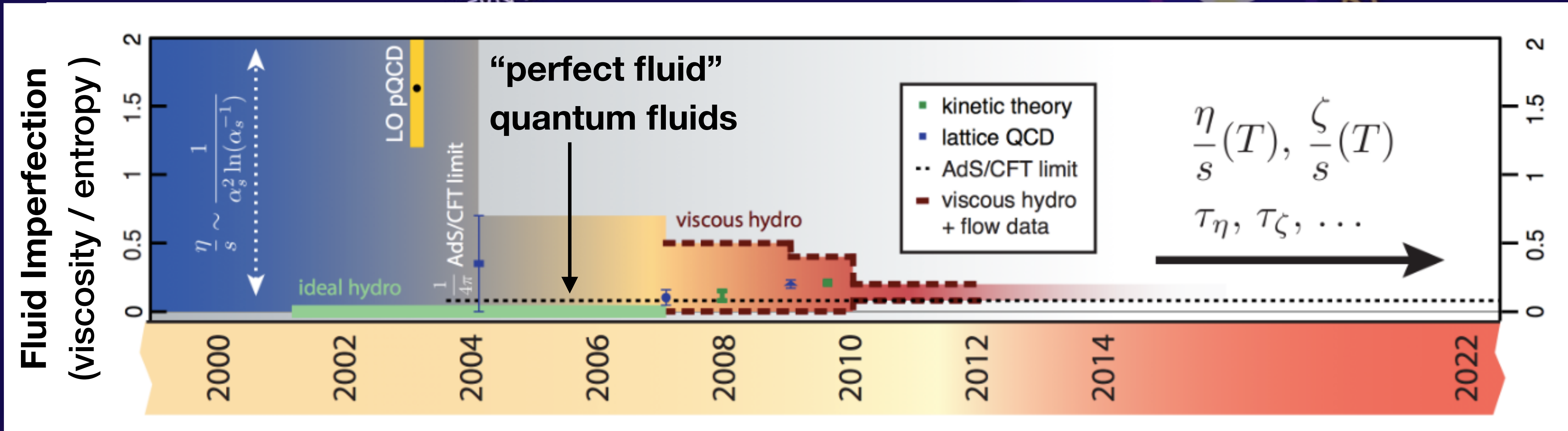
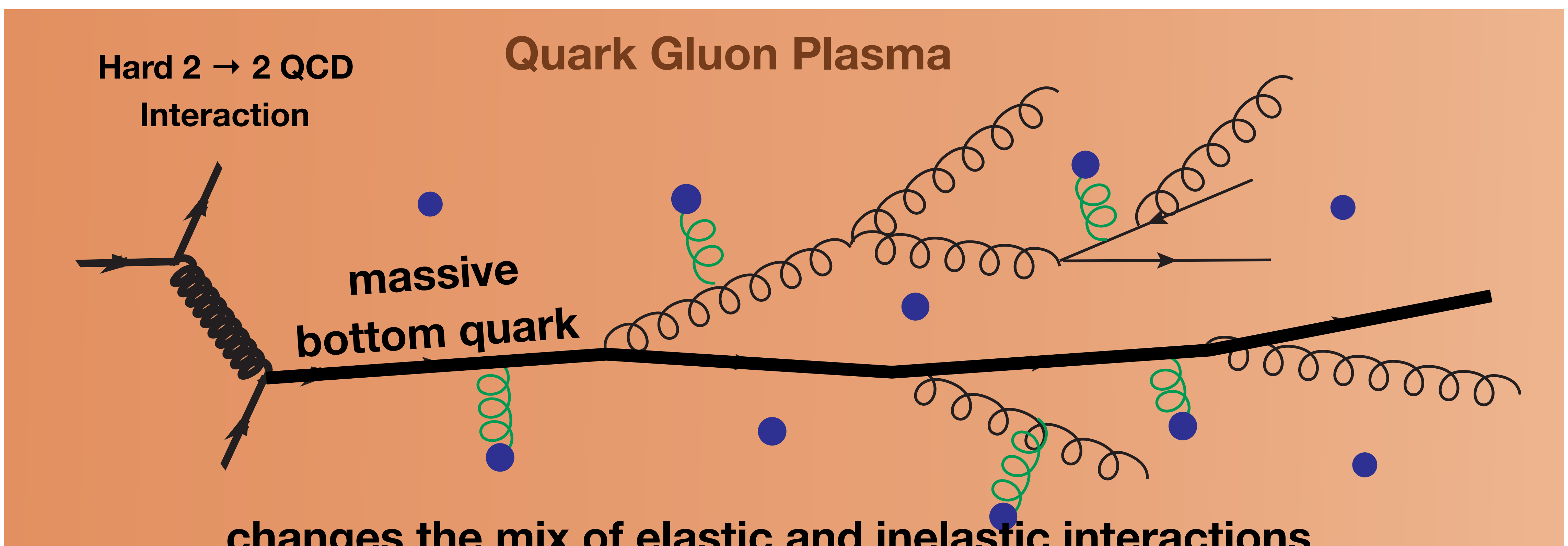
Macroscopic Picture of the Quark Gluon Plasma



Microscopic Picture of the Quark Gluon Plasma ??



Interconnection of pixel chip to flex PCB

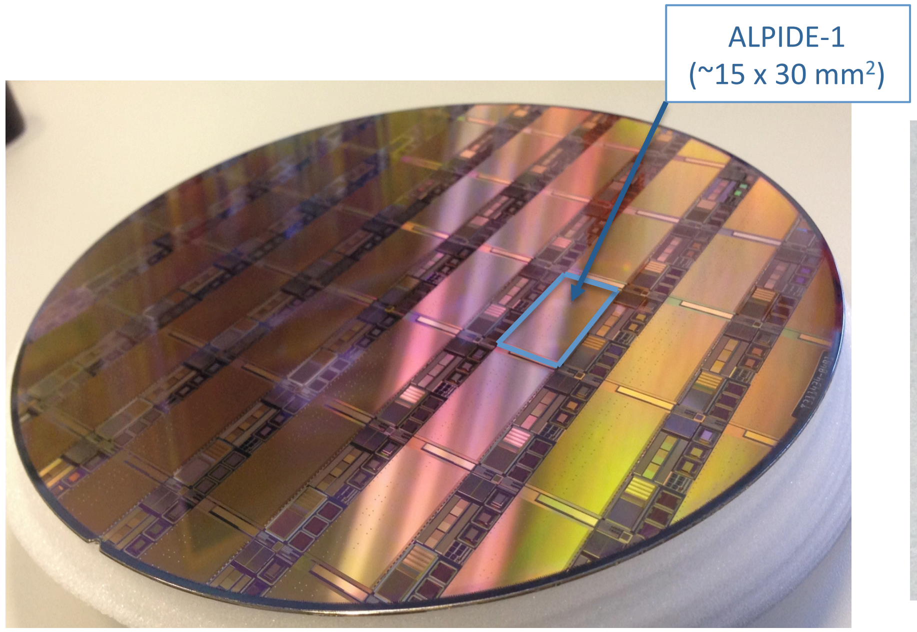
A Large Ion Collider Experiment

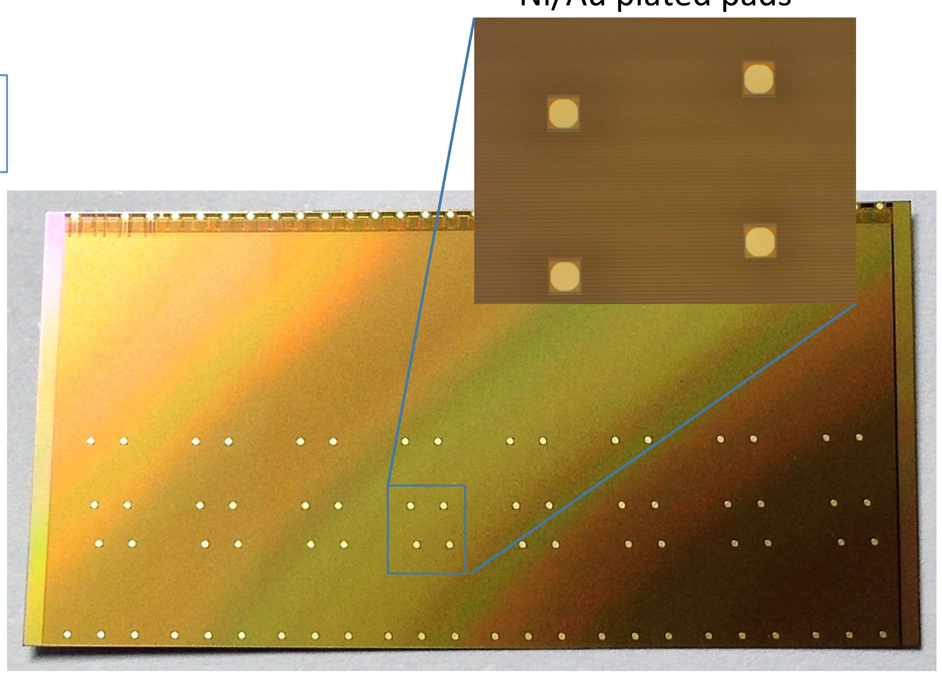
ALICE

Solder Pads

In order to solder the chip on the flexible printed circuit (FPC), the chip Al pads need to be covered with Ni-Au (wet-able surface)

Plating is done on wafers level using electroless Ni-Au plating, prior to thinning and dicing



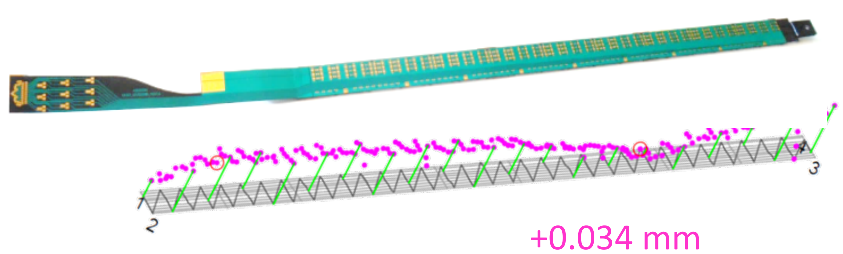


Contact pads are distributed over the matrix (custom designed)

Inner Barrel Stave

Stave HIC+ Space frame assembly

Dimensional accuracy

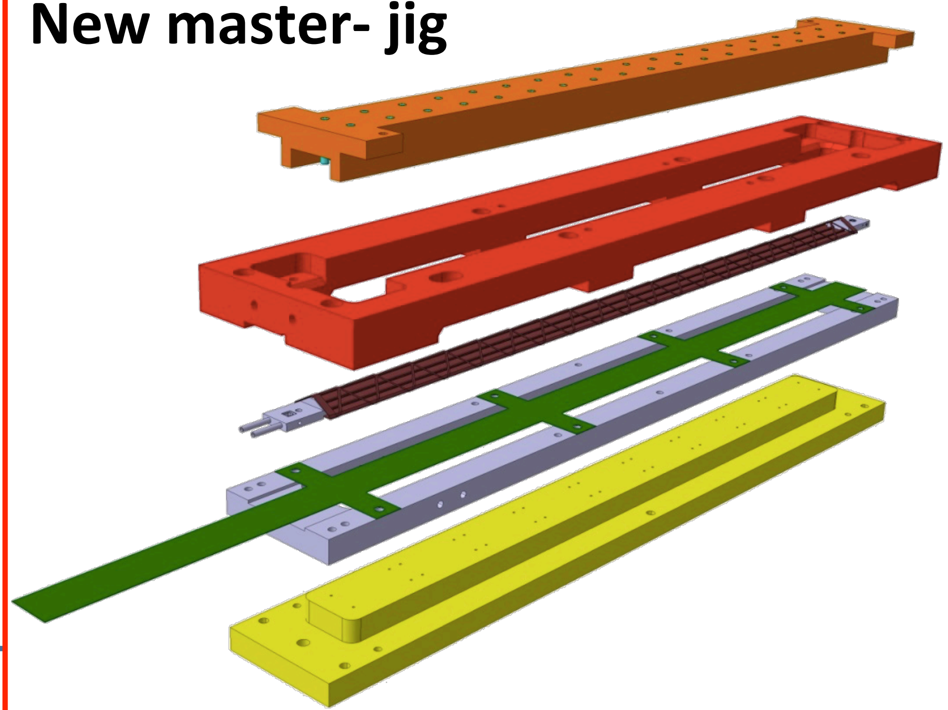


+0.034 mm
- 0.034 mm

status

New master jig (ready) will improve stave accuracy

New master- jig



ongoing

New master jig produced and shipped from the Company, metrological verification ongoing

Space frame production

status

Available : n. 20 spaceframe

Ongoing

pre-production continues to prepare for final series production

Layout and curing process optimization: planarity achieved ± 0,028÷0,040 mm

MAPS Geometry

from the pCDR:

Layer	radius (cm)	pitch (μm)	sensor length (μm)	depth (μm)	total thickness X_0%	length (cm)	area (m^2)
1	2.4	28	28	50	0.3	27	0.041
2	~4	28	28	50	0.3	27	~0.068
3	~6-15	28	28	50	0.3	~27-39	~0.102-0.368

3 layers will probably be needed to define the track position and curvature for a 2nd vertex reconstruction, can be done within the material cost of 1 VTX pixel layer

Similar inner layer positioning, just outside our beam pipe

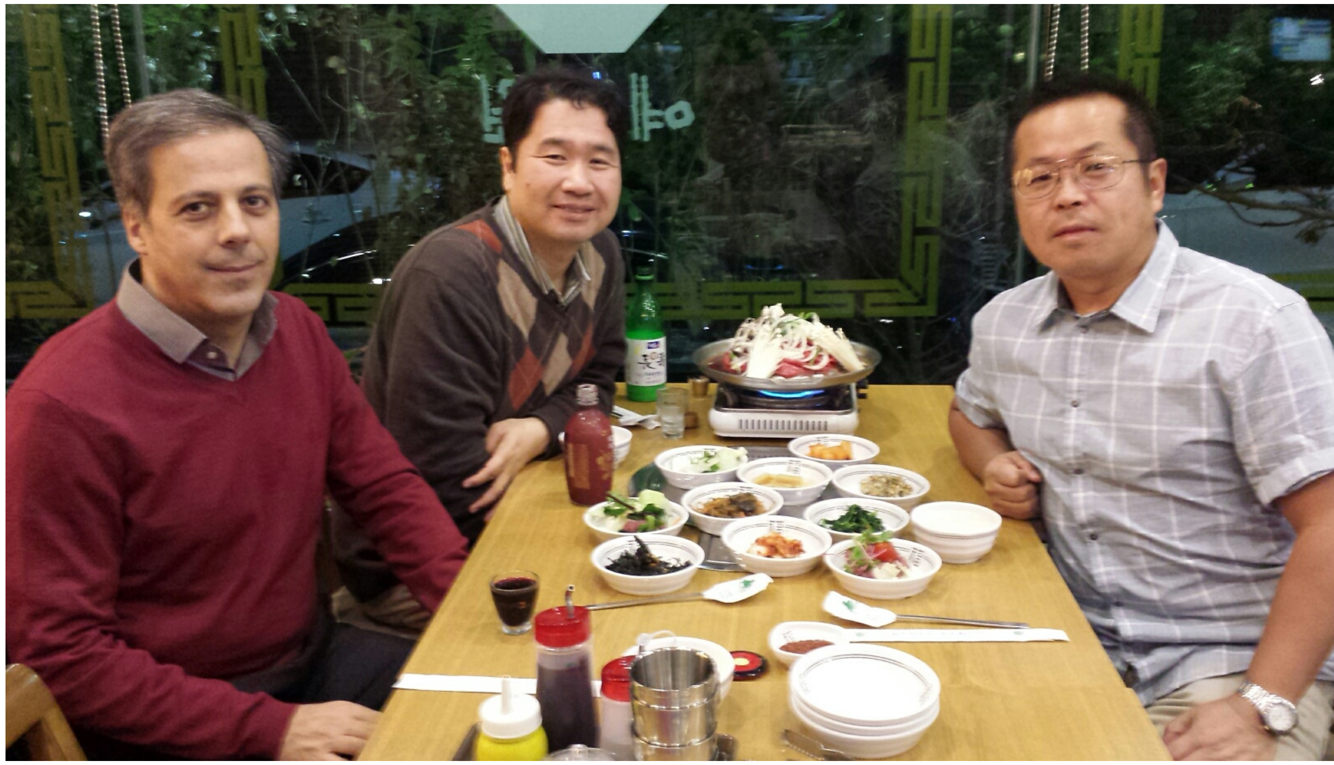
Outer staves could sit as far as 6 cm from the beam pipe before a longer than 27 cm ladder arrangement is needed—as dictated by vertex⊗eta coverage.

Optimizations between track position requirements and pattern recognition could force the outer layer out farther, depends on outer tracker design

We started with the more compact (2.4,4,6) version…

Making the MAPS a Reality

- Had good discussions with Luciano Musa and Yongil Kwon in Korea during K/J sPHENIX workshop
  - CERN will provide a few chips with readout cards "immediately" for sPHENIX/LANL R&D
  - For the final sPHENIX project, share the R&D cost with ALICE (~$2.5M) accordingly to the size of detectors (~$250K?)



- Plan to visit Berkeley(or CERN) to learn about the operation, and get help from them to start R&D at LANL

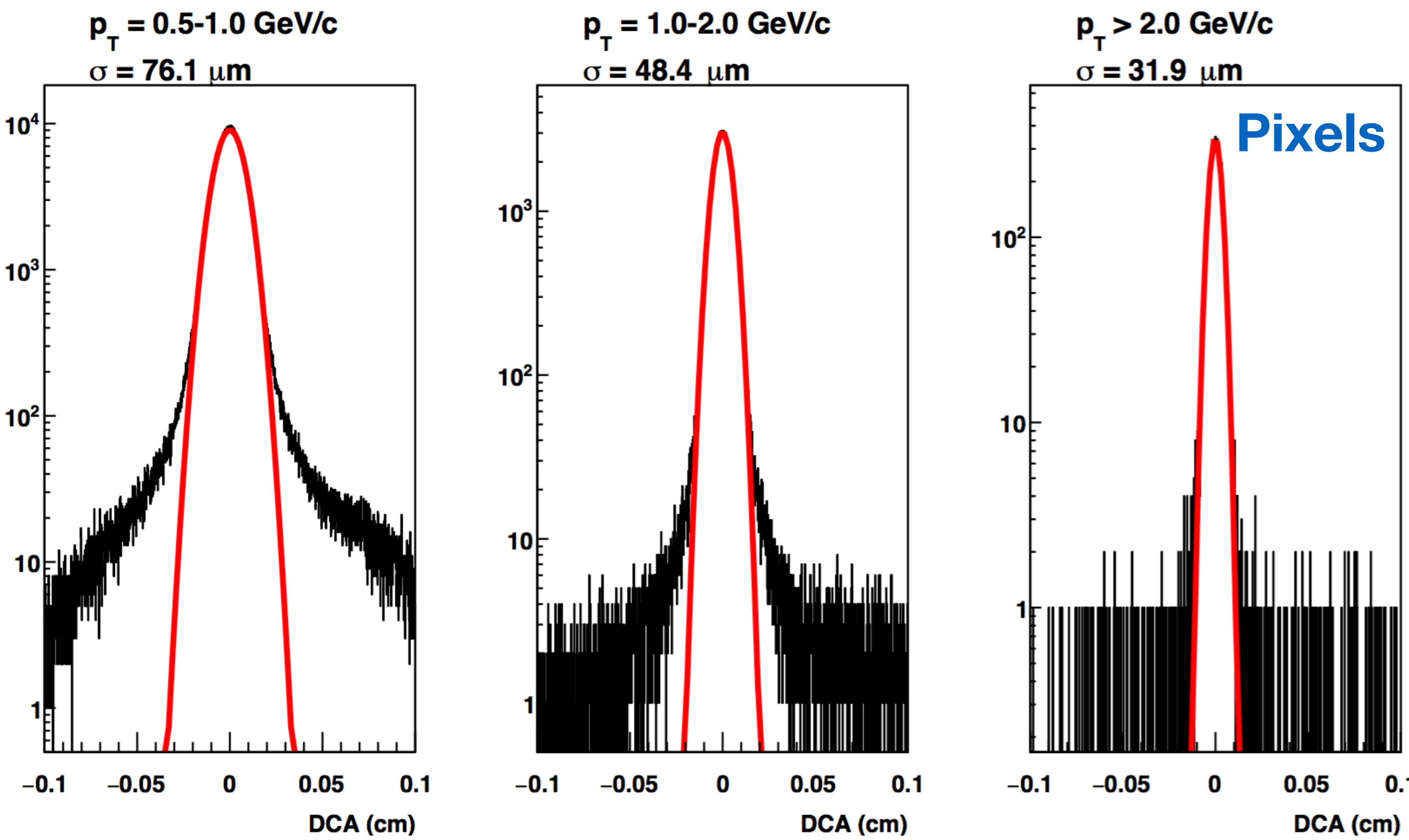
- Possible collaboration with Korea institutes to provide MAPS chips for sPHENIX inner pixel detectors
  - Korea funds:
    - MAPS chips
    - Production test, assembly etc.
    - A few $100K possible (new proposal)
  - LANL/US provide ROC/FEM
    - LANL LDRD/DR?
    - ~$1M ? (take advantage of ALICE ROC design etc., minimal R&D)

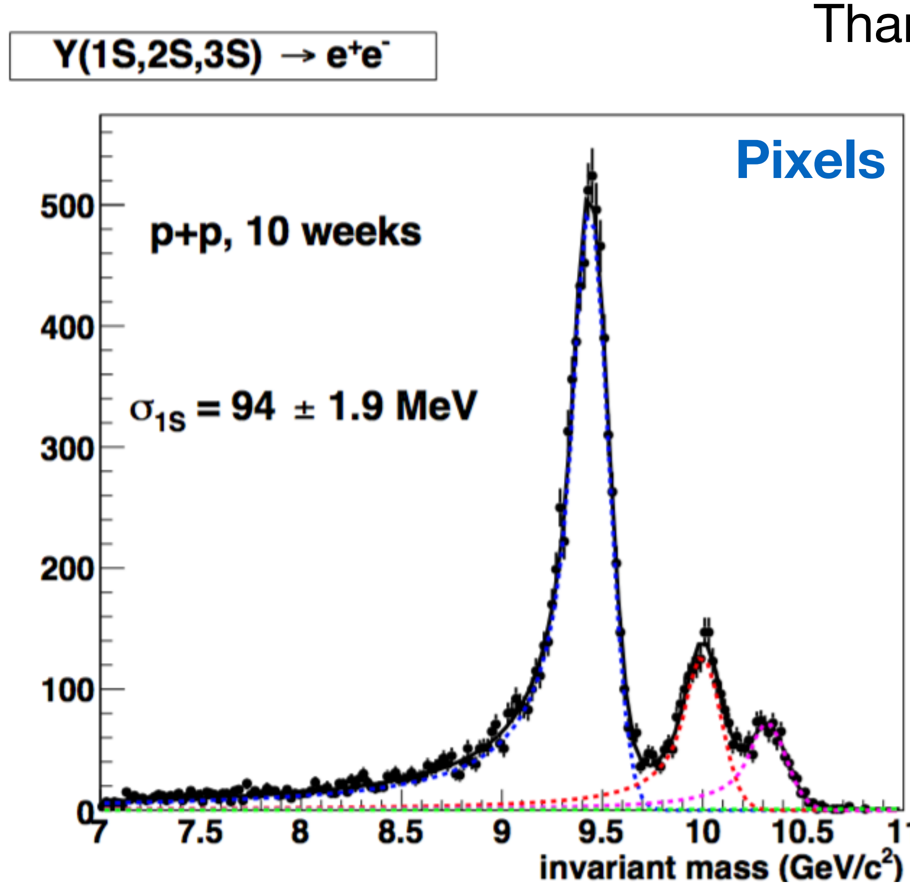
sPHENIX inner pixel detectors:
R = 2.5/4.0/6.0 cm
Z = +/-50cm
Area = 2*pi*R*Z
= 7,850 cm^2 = 0.8 m^2

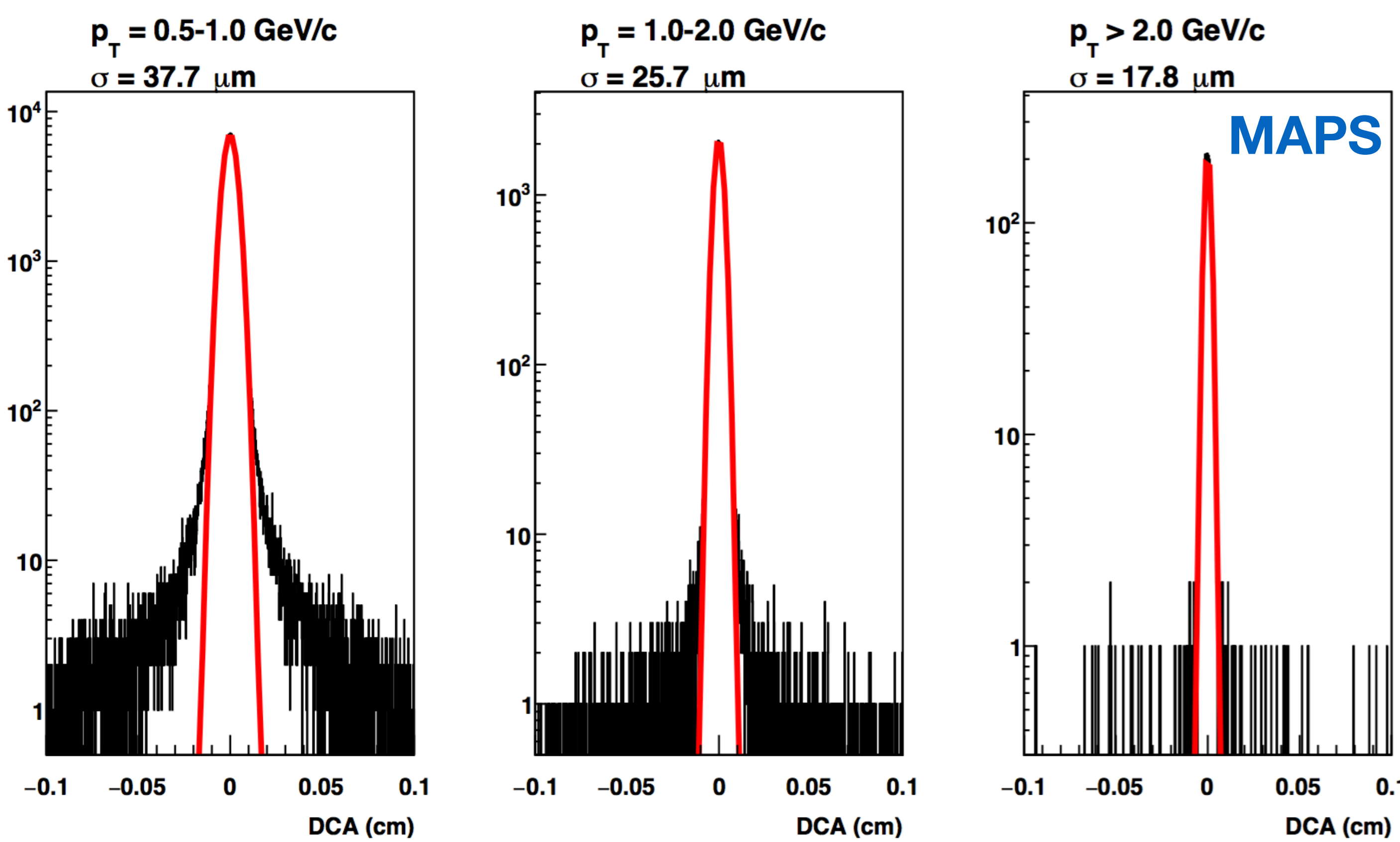
Chip = 15mm x 30mm = 4.5 cm^2
7850/4.5 = 1750 chips
Wafer = 48 chips/$2K -> $73K

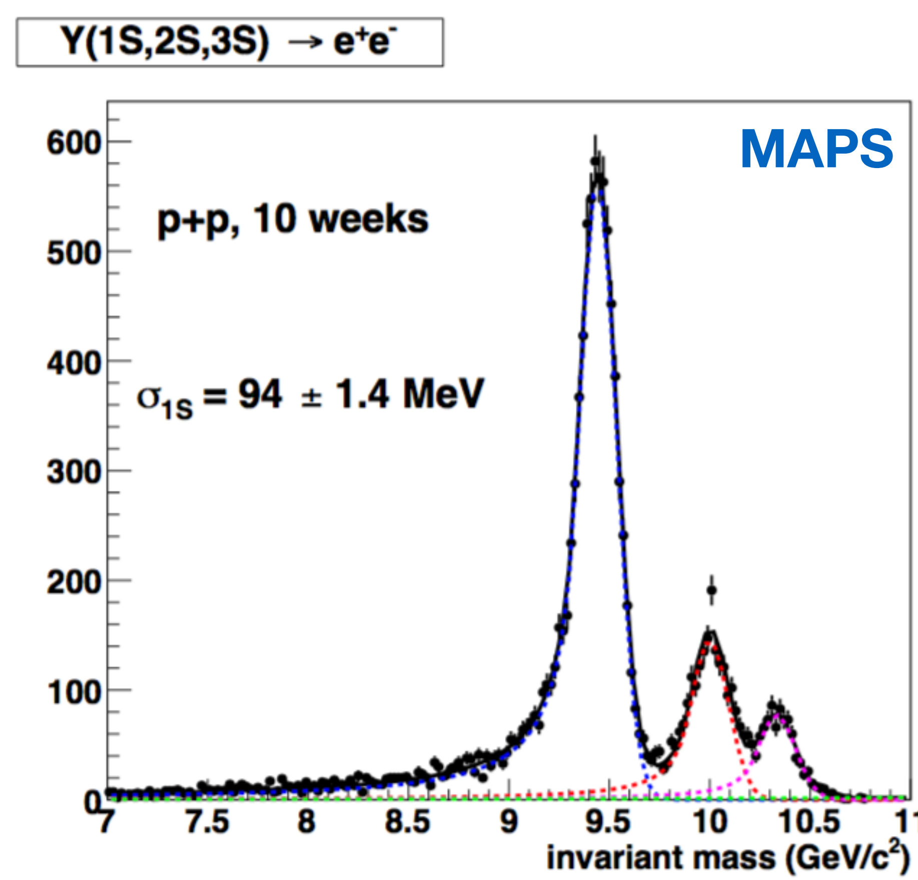
pCDR Performance Plots

Thanks TF!



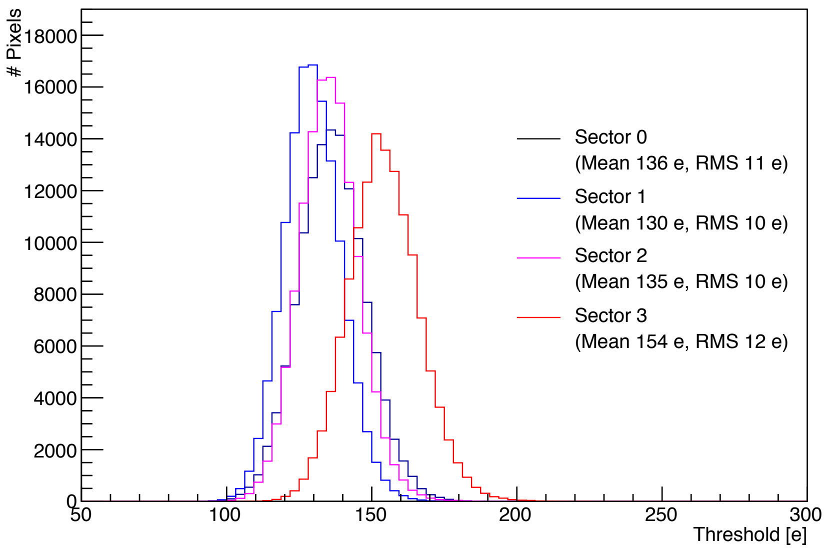


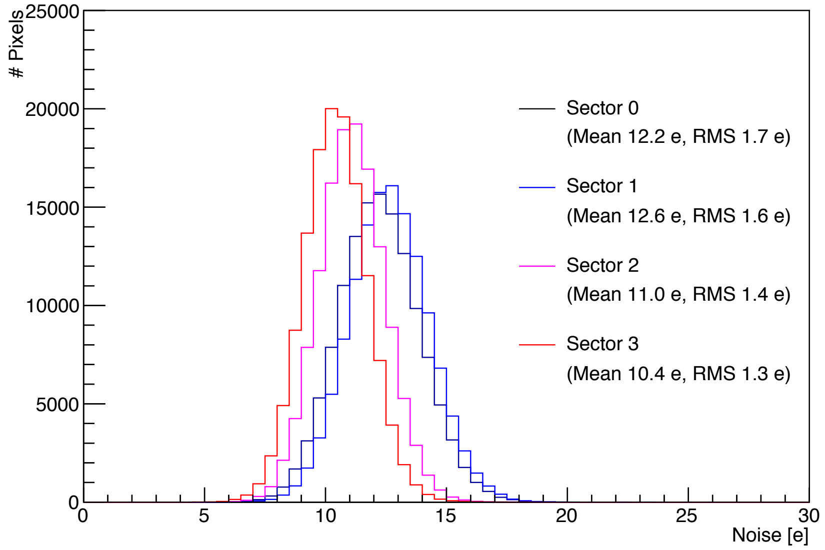




ALICE

Example of Threshold and Noise Distributions





V_{SUB} = -3V, I_{THR} = 0.5nA, V_{CASN} = 0.95V

- All sectors behave qualitatively similarly
- Noise is about the same value as threshold RMS
- Threshold about 10 x higher than noise
- Threshold 7 x smaller than most-probable energy loss signal of a MIP in 18μm of silicon

Missing Detector Requirements

What does our Proposal and pCDR say about b-jet id:

Heavy quark jets The key to the physics is tagging identified jets containing a displaced secondary vertex

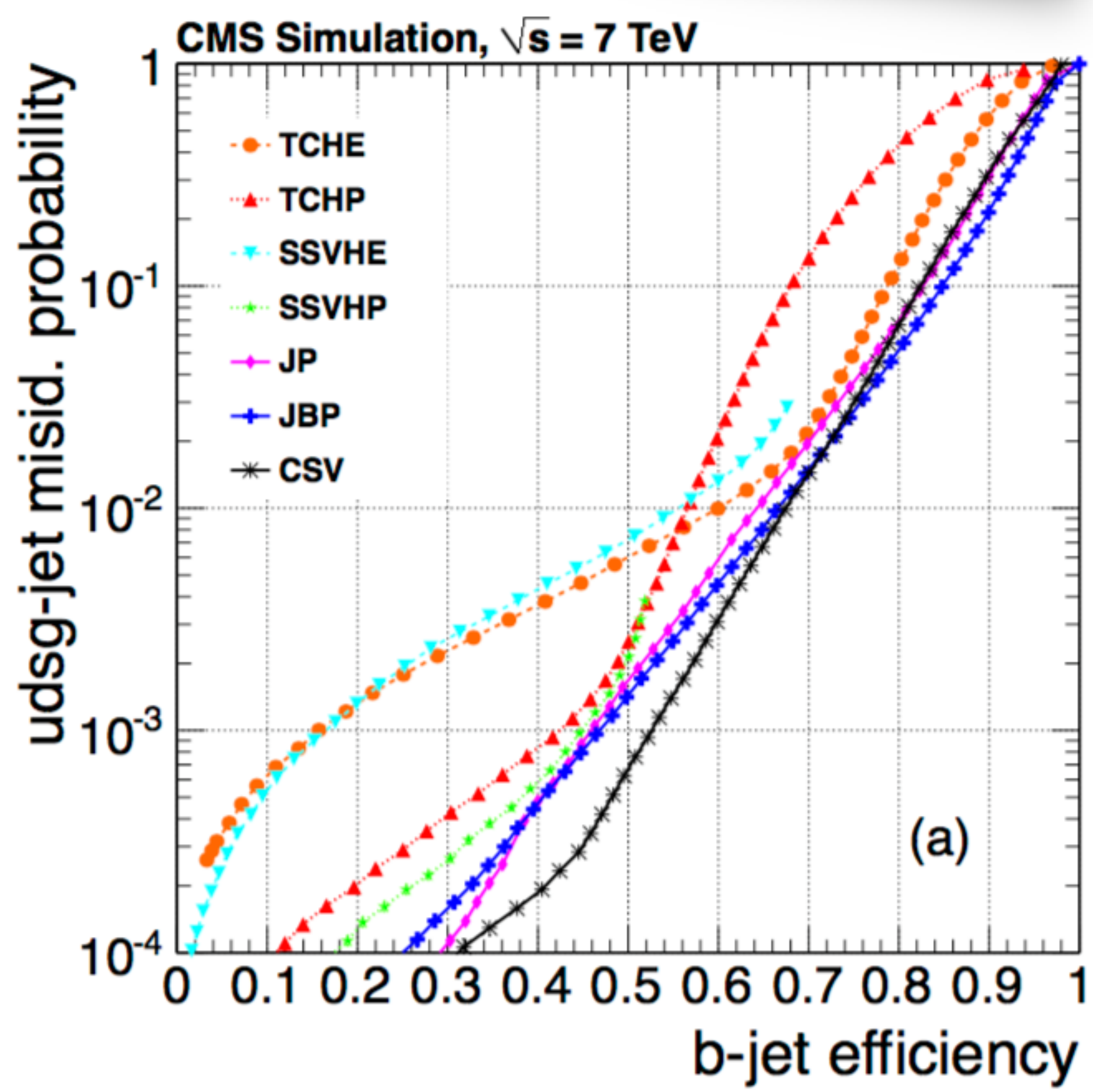
- precision DCA (< 100 microns) for electron $p_T > 4\,\mathrm{GeV}/c$
- electron identification for high $p_T > 4\,\mathrm{GeV}/c$

The current spec doesn't define a purity/efficiency requirement and focuses only on the semi-leptonic channel for some bizarre reason.

We will need to add either:

(1) charged particle tracking efficiencies
(3-track counting: ~95% will be needed)
(2) track position resolutions / better IP resolutions
(2nd vertex CMS IP resolutions ~15-30 um)
(multi-DCA needs ~70 um)

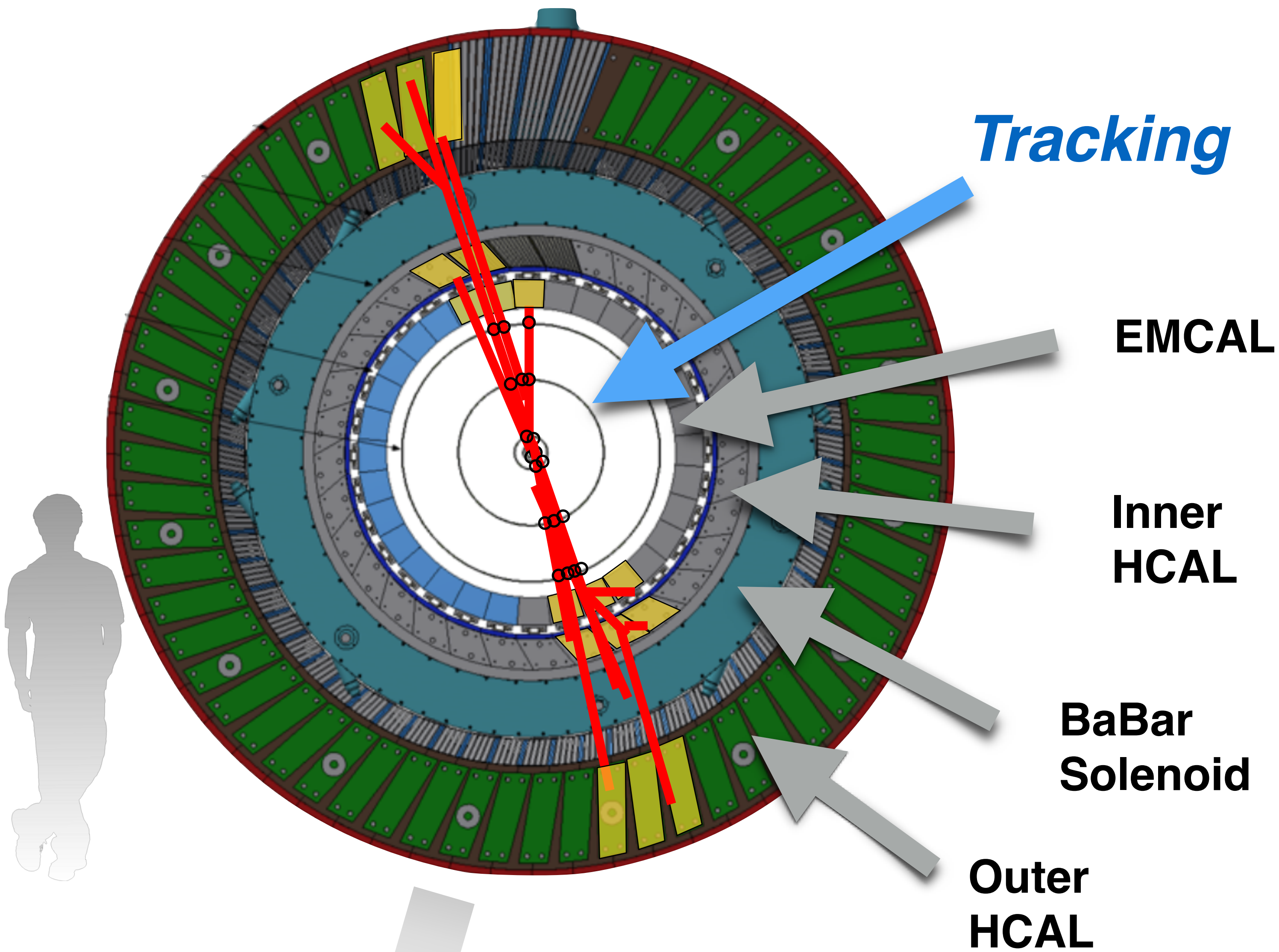
Or more generally, we should define a spec for:
(A) B-jet identification purity (contamination) and efficiency requirement
(We argued in April that:
~45% efficiency and ~35% purity in Au+Au would be comparable to CMS)

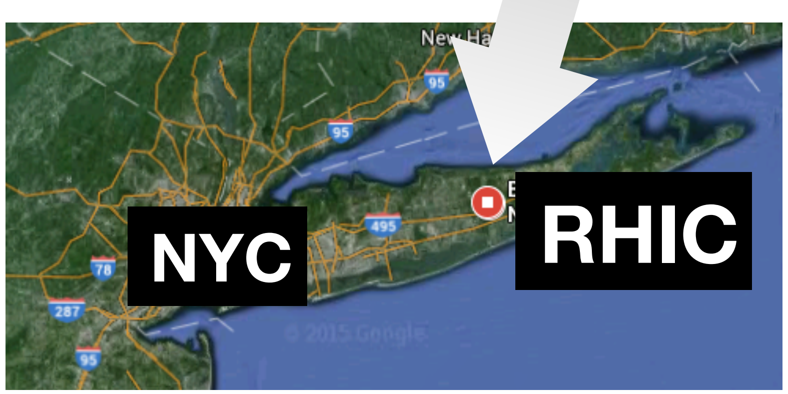


It is a big (unavoidable) job to connect these different methods and the physics to detector requirements but we can use CMS-inspired numbers in the interim

sPHENIX Proposal: nucl-ex/1501.06197

Jets and Upsilons at RHIC in 2021 & 2022





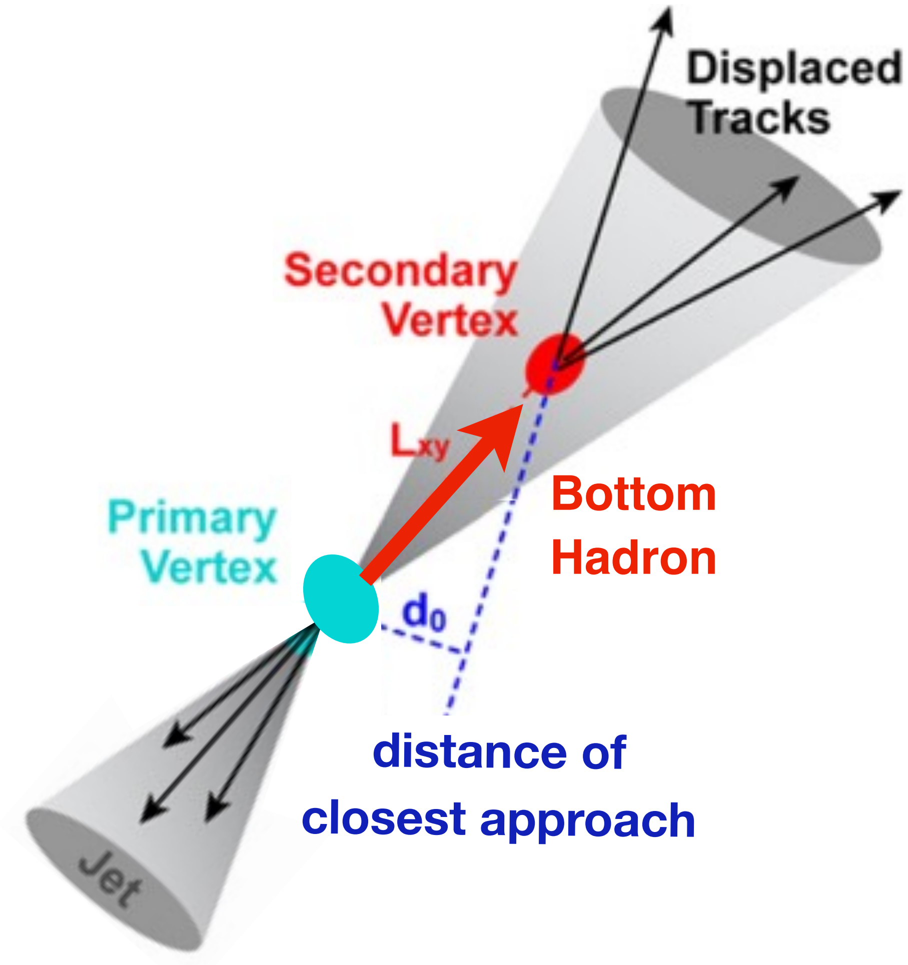
Physics:** study of QGP structure over a range of length scales and temperatures with **hard-scattered probes inc. bottom quark jets

*"[sPHENIX] presented **a compelling physics program.**"*
~ sPHENIX DOE Science Review Committee

*sPHENIX **highlighted in Hot QCD Long Range Plan***

Inaugural Collaboration Meeting
*Rutgers Dec 10-12th, **~60 institutions***

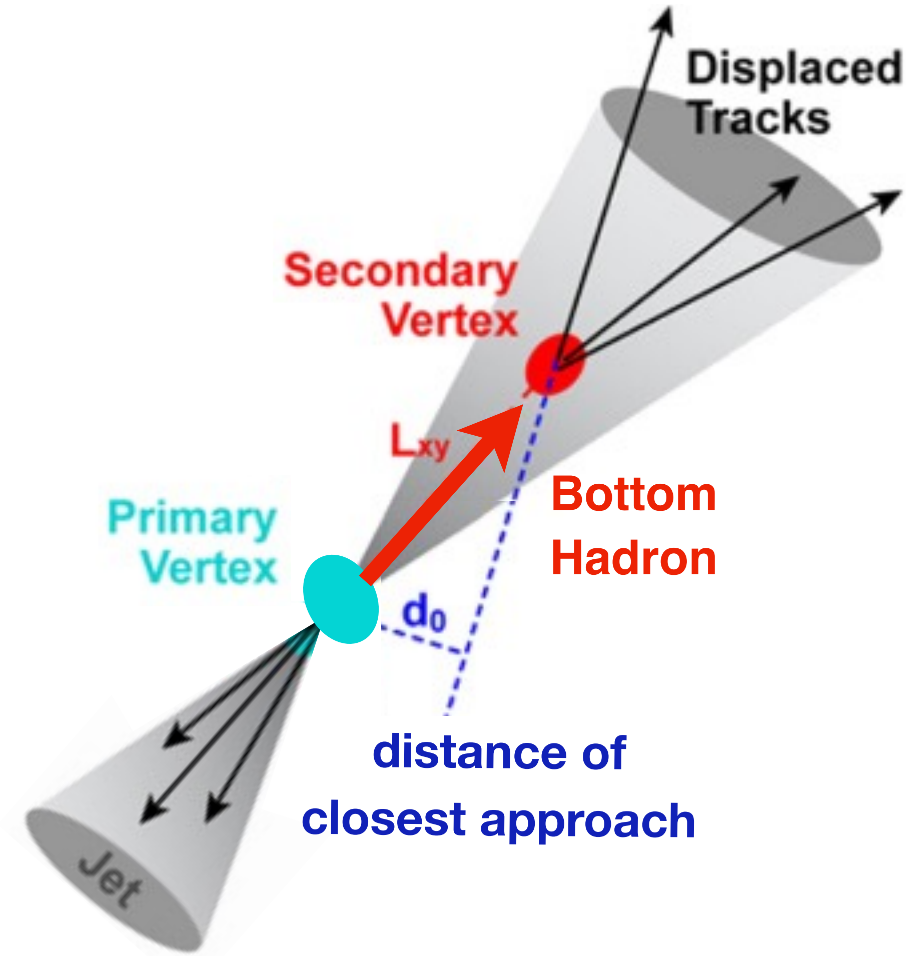
Impact of a LANL Contribution



High Precision High Efficiency Charged Particle Tracker Needed by sPHENIX for Bottom Jet Identification

P-25 expertise on silicon tracking ideally suited for this role and sPHENIX project management craves LANL leadership

Impact of a LANL Contribution



High Precision High Efficiency Charged Particle Tracker
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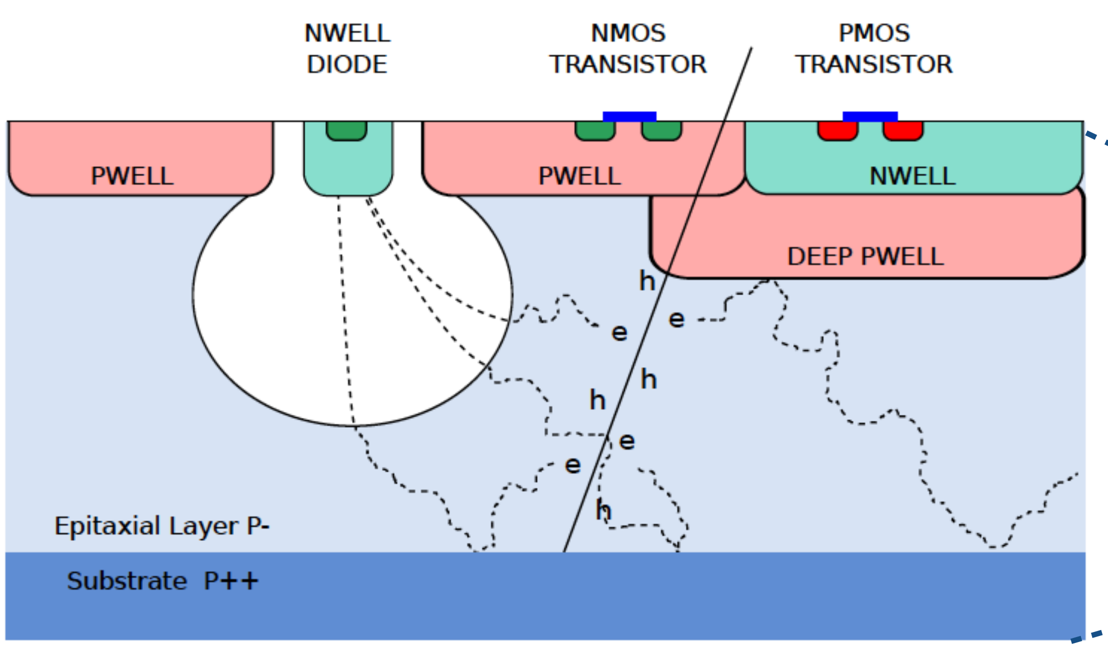
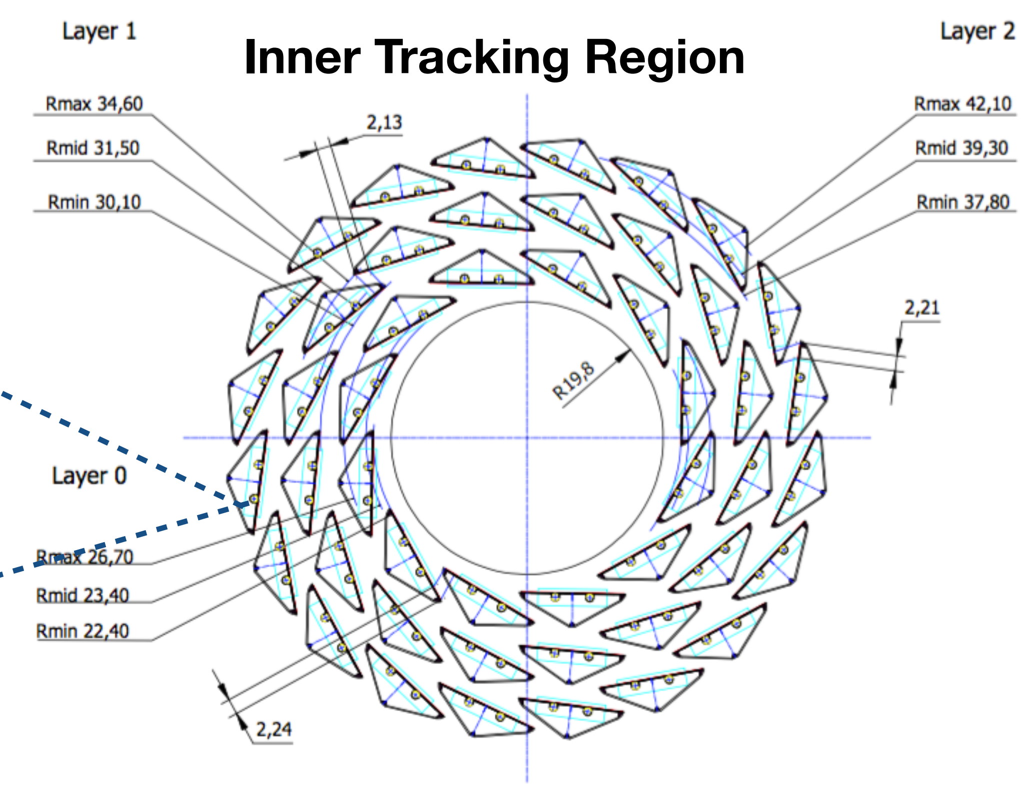
Inner Silicon Concept with Monolithic Active Pixel Sensors:
- Very fine pitch (<30x30 um), large efficiency (>99%)
- Optimizations for material thickness, ~0.3%/layer





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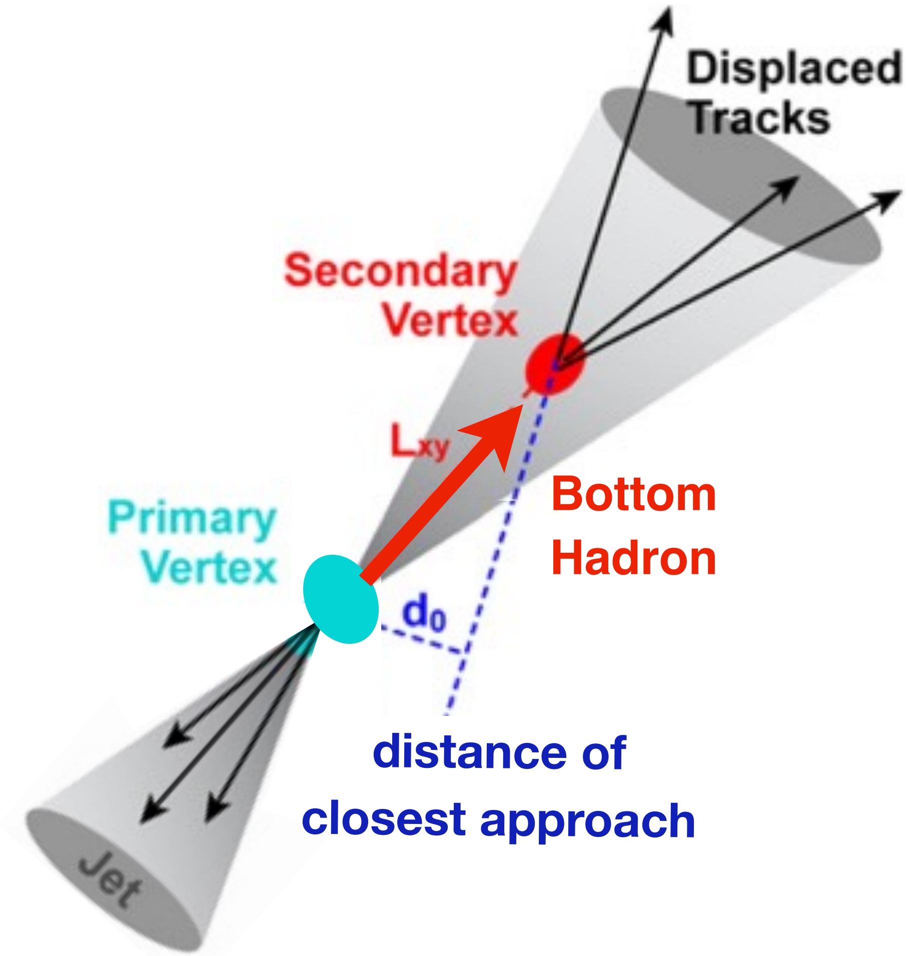

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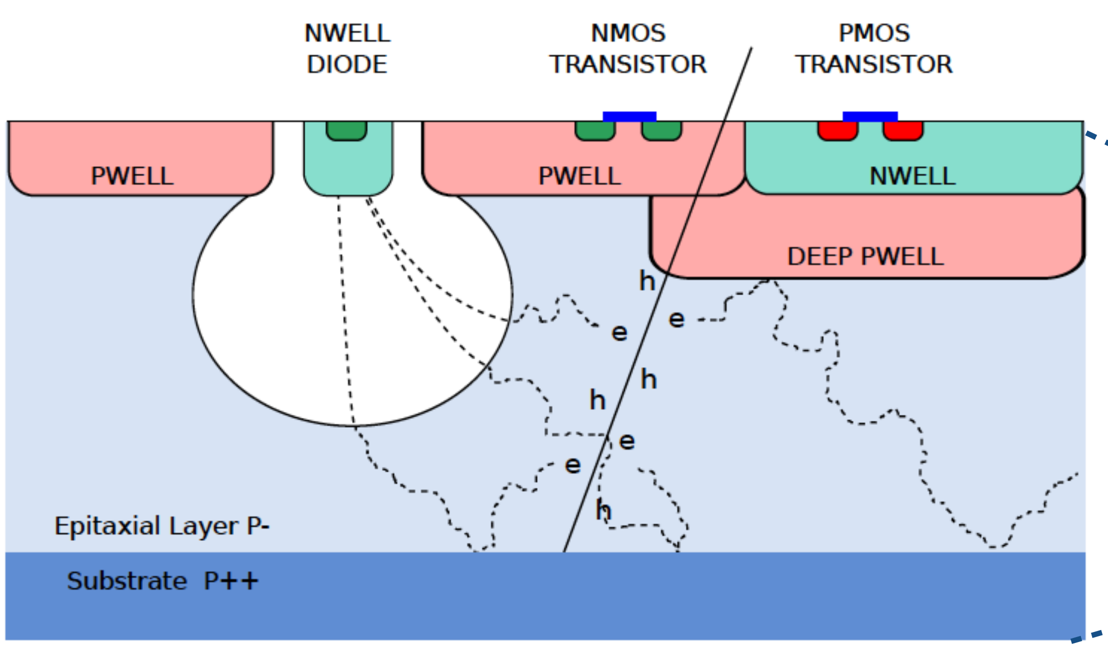

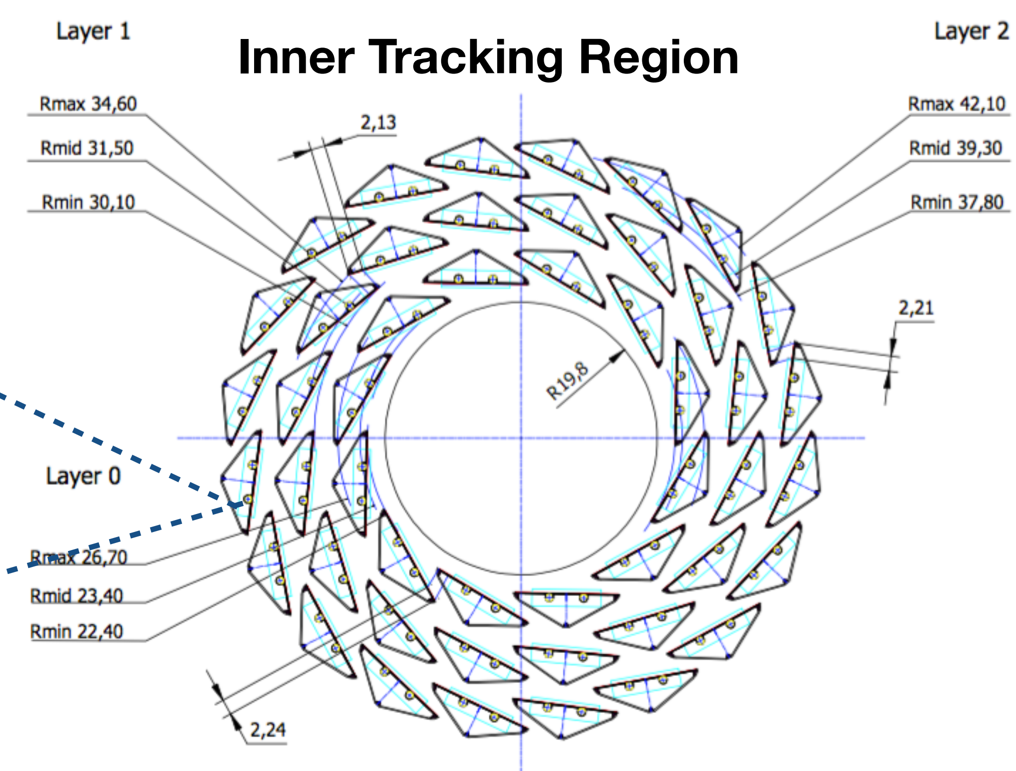

T-2 expertise on heavy quark and jet calculations is needed to support this effort